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Armored Composite Ammunition Pressure Vessel

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14. ABSTRACT
Report developed under Phase I Small Business Innovation Research (SBIR) contract M67004-99-C-0020. This program focused on the development of an advanced ammunition containment system for the Advanced Amphibious Assault Vehicle (AAAV). This ammunition containment system must not only meet environmental and handling requirements but also provide armor protection against impacting threats and reduce the response of the stowed ammunition to an acceptable level when encountering an overmatched threat. The design of the ready ammunition box and feed system was accomplished by an integration of advanced armor-system and composite rocket motor casing technologies. The integration of these two technologies is essential since both ballistic protection and containment of high-pressure gases are simultaneously required for proper functioning of the containment system. In the event of an overmatched threat engagement, during which the stowed ammunition react, our proposed ammunition system concept will contain the internally generated fragments and gases, to allow for venting of the gases to the exterior of the vehicle.

15. SUBJECT TERMS
Ammunition containment, fragmentation, pressure retention, armor, composite, AAAV ready container

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I. Executive Summary

This Phase I Small Business Innovation Research (SBIR) program addressed the development of an advanced ammunition containment system for the Advanced Amphibious Assault Vehicle (AAAV). The objective of the Phase I program was to develop a containment design concept for the ready ammunition container and feed system which provides armor protection against impacting threats and contains the overpressure and toxic gases generated from an overmatching threat. Compatibility with the provided AAAV ammunition container and feed system design and operational requirements was established as a critical design constraint. Since specific cost and weight constraints were not provided until the Phase I design and feasibility study were concluded, the design approach taken in Phase I was to develop an ammunition containment system which provides the maximum level of performance against the worst case threat condition. Each component of the system was sized to withstand the maximum loading conditions expected with high positive margins of safety. Given specific cost and weight goals, a much lower cost, lighter weight system could be designed to meet acceptable, although less stringent, performance criteria.

Design development and analyses were performed in Phase I to establish a prototype design concept and demonstrate performance in accordance with the program objectives. Specifically, analyses were performed to: define the loading environments associated with medium level and higher level threat engagements for the provided AAAV ammunition configuration; establish armor thickness requirements and evaluate armor protection; define and evaluate performance of a burst-open venting system; evaluate energy absorption capability of the proposed wall configuration; and identify materials and thicknesses and evaluate the structural performance of a composite containment wall design. In addition to the analyses, solid models of the prototype containment system design were generated for design presentation and for estimating volume and weight.

The design of the ready ammunition box and feed system containment structure employs a multi-layer, armored composite wall that provides multi-functional capabilities of armor protection, energy absorption, blast protection, sealing and pressure retention. Although the ammunition-ready container was of primary concern for the Phase I effort, conceptual designs were also developed for the feed system containment in a manner consistent with the design approach for the ready container. Since specific weight and cost constraints were not provided during the Phase I program, a generally conservative approach using only currently demonstrated materials and technologies was used to determine the most appropriate solution.

The design of the ammunition containment system was divided into two tasks, armor design and pressure containment. The armor design effort focused on fragment protection and energy absorption. The pressure containment effort focused on the selection of materials and composite lay-up required to contain the quasi-static pressure loading. Hydrocode analyses was performed to determine foam densities and thicknesses for energy absorption. Three-dimensional finite element analyses of the ammunition

ready container pressure wall were performed to evaluate different wall thicknesses and structural reinforcement configurations.

The recommended containment wall design resulting from the Phase I analyses is as follows: 0.25 inch Armor Steel (interior)/0.125 inch EPDM Rubber Seal Layer/ 0.125 inch S-2 glass/epoxy/ 0.5 inch Foam (20pcf)/0.50 inch S-2 glass/epoxy. An external steel frame was used to provide localized reinforcement to the composite wall and allow attachment locations for the doors and access ways.

In conclusion, the Phase I research program has demonstrated the technical feasibility of developing a multi-layer armored composite ammunition containment system for the AAAV. The results of the design development and analyses performed in Phase I have shown that a containment system including inner steel armor, energy absorbing foam and S-2 glass/epoxy composite pressure retention layers can be designed to provide the desired armor protection against impacting threats and reduce the response of the stowed ammunition to an acceptable level when encountering an overmatched threat. The multi-layer, armored composite ammunition containment system provides multi-functional performance capability of Armor Protection, Energy Absorption, Pressure Containment and Pressure Retention. This increased protection of ammunition within the combat vehicle will improve the vehicle's ability to carry out its mission with a reduction in both the risk to the crew and the vulnerability of the vehicle

The Phase I research effort has provided a significant foundation for further development and demonstration of a prototype ammunition containment system for the AAAV. Specific requirements must be established in coordination with USMC and General Dynamics to identify weight, space and cost constraints for the containment system. Further development and testing is recommended to size the steel, composite, and foam wall thicknesses and demonstrate the performance of the elastomeric seal layer. Sub-scale testing is recommended to validate the armor concept for blast and fragment protection. Full-scale controlled pressure tests are required to validate the structural integrity of the S2 glass/epoxy containment wall. Further development of the ammunition feed rail and gun feed containment is also required. Manufacturing of a prototype HE/AP ready container is recommended to demonstrate manufacturing feasibility. Loading and structural conditions of the turret shelf and gun feed system require further analysis prior to development of final design details.

II. Design Considerations

The objective of the Phase I design effort was to develop a ready ammunition container configuration which would prevent the propellant gases from leaking into the AAAV's combat vehicle crew space in the event of an overmatched threat. The design must also provide additional armor protection against medium level threats. The desired result for an overmatch threat engagement is to reduce the response of the stowed ammunition to an acceptable and safe level by preventing ejection of burning munitions and fragments from the container into the crew compartment. The system will then vent the gases to the exterior of the vehicle maintaining a safe environment inside the vehicle.

The ammunition-ready container was of primary concern for this Phase I effort with the storage containers and the feed system as secondary concerns utilizing the same containment design approach as in the ready container design. The majority of the effort in the Phase I program was focused on the design of the High-Explosive (HE) ammunition ready (or stowage) container.

Since specific weight and cost constraints were not provided during the Phase I program, a conservative approach using only currently demonstrated materials and technologies was used to determine the most appropriate solution. Weight and space were considered to be at a premium in the vehicle overriding cost as a consideration for system implementation.

A set of turret drawings were received from General Dynamics at the onset of this program. Representative portions of these drawing are presented in Figure 1. The configuration presented in this drawing set was used as the baseline departure point for the design effort. The drawings were reviewed to establish the container and feed system dimensions and space constraints. The containment system design was developed to be compatible with the provided turret configuration, with the assumption there could be no change to the design of the AAAV's Firepower system.

The containment system configuration was envisioned to consist of three main compartments, as shown in the solid model sketch in Figure 2. The first compartment is the ammunition storage box, which consists of the HE and AP ammunition area. Access to this compartment is provided by doors attached to the top of the compartment opening upward. The second compartment encloses the feed system. The access doors for this compartment would be located on one of the vertical surfaces. The last compartment would enclose the upper section of the feed system leading to the gun. This area must allow movement of the gun assembly while maintaining a tight pressure seal.

The containment system design for each of the compartments consists of three sub-systems: (1) Armor Protection, (2) Pressure Retention, and (3) Venting System. A multi-layer wall configuration was used to accomplish these tasks. A sketch of the multi-layer wall configuration is presented in Figure 3. The interior layer of the wall is the armor protection. The armor layer will provide protection against medium level threats and contain the internally generated fragments from the stowed rounds in the event of an

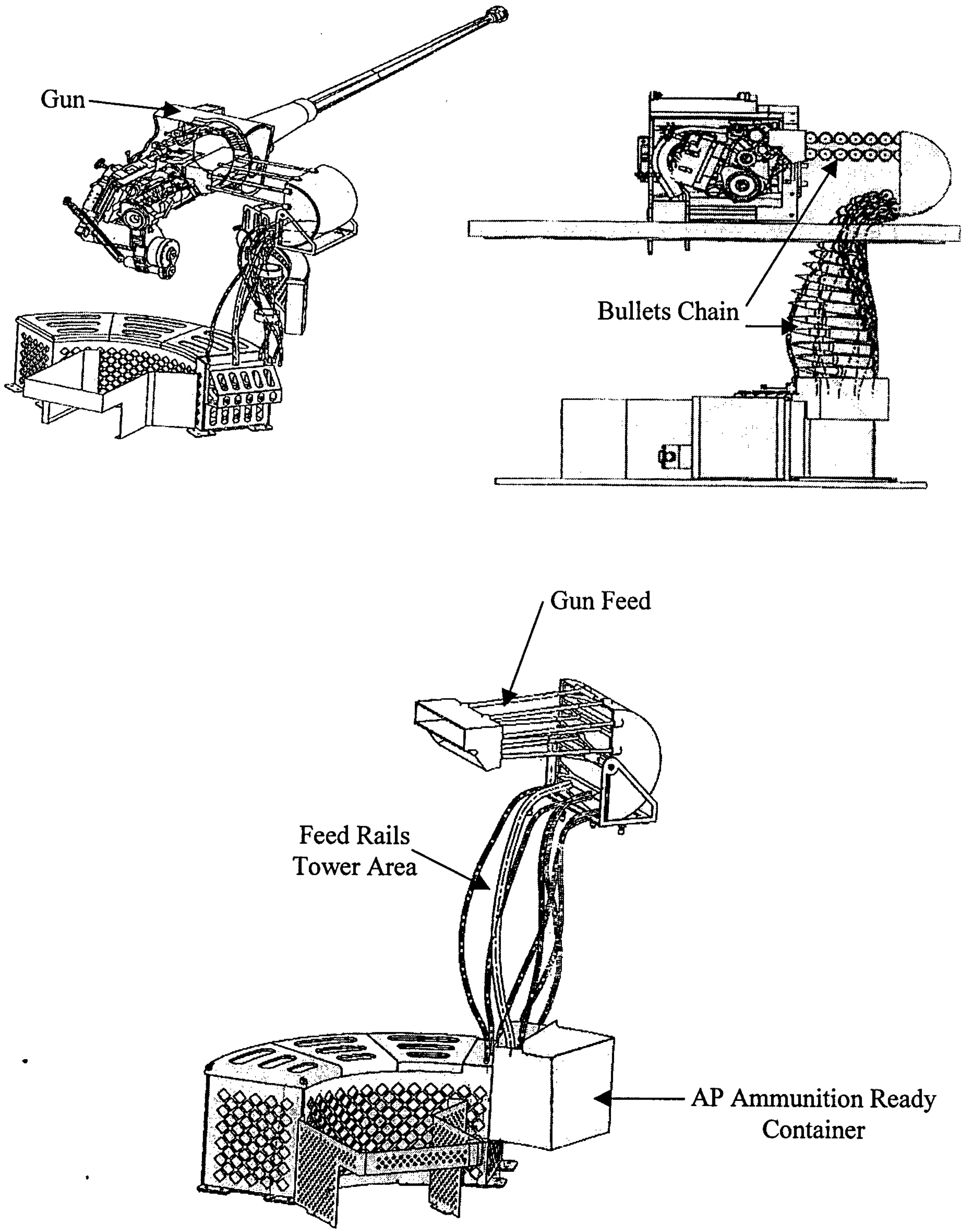
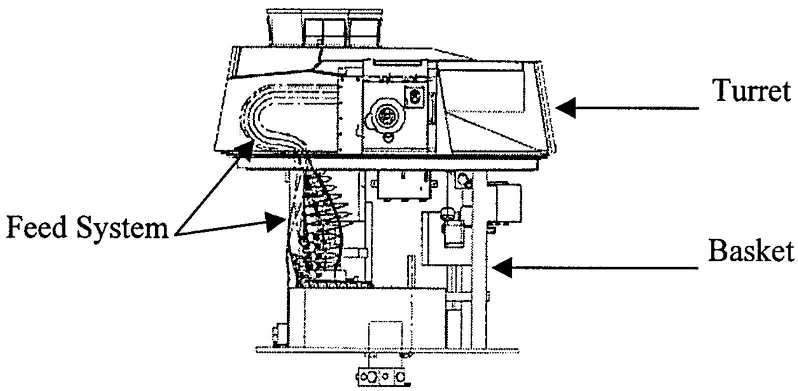


Figure 1. General Dynamic's turret configuration drawings.



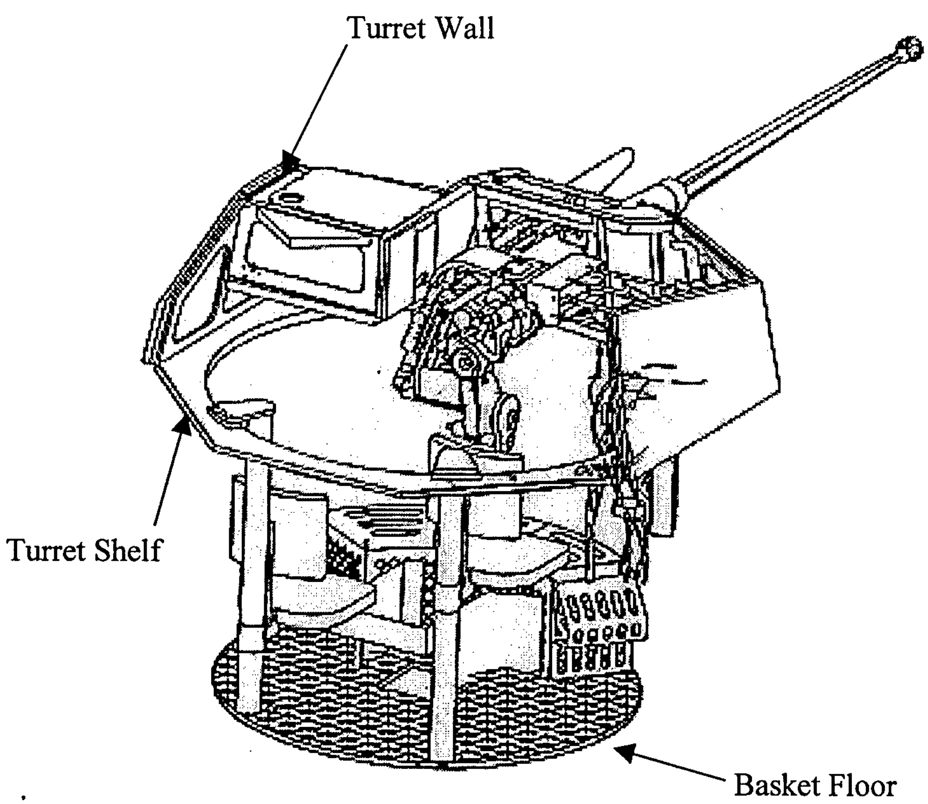


Figure 1. (continued) General Dynamic's turret configuration drawings.

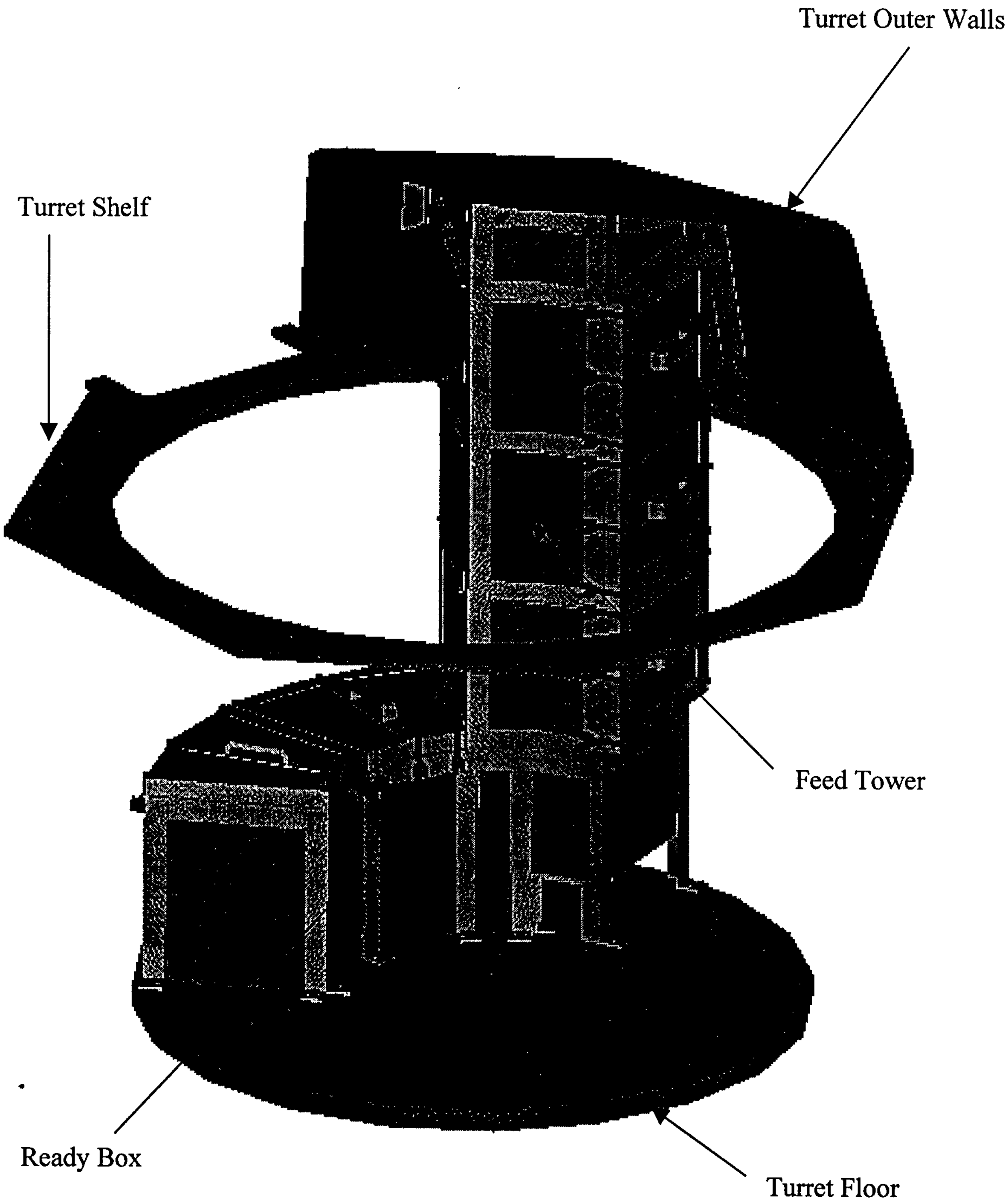


Figure 2. Solid Model of proposed containment system configuration consisting of three main compartments.

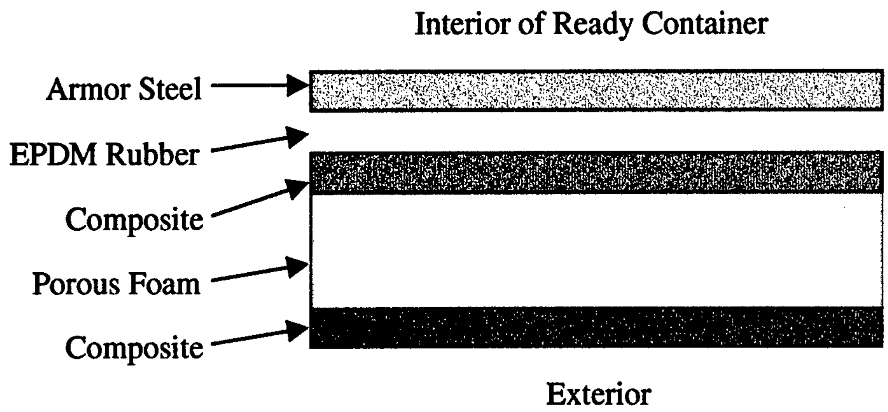


Figure 3. Sketch of multi-layer wall configuration.

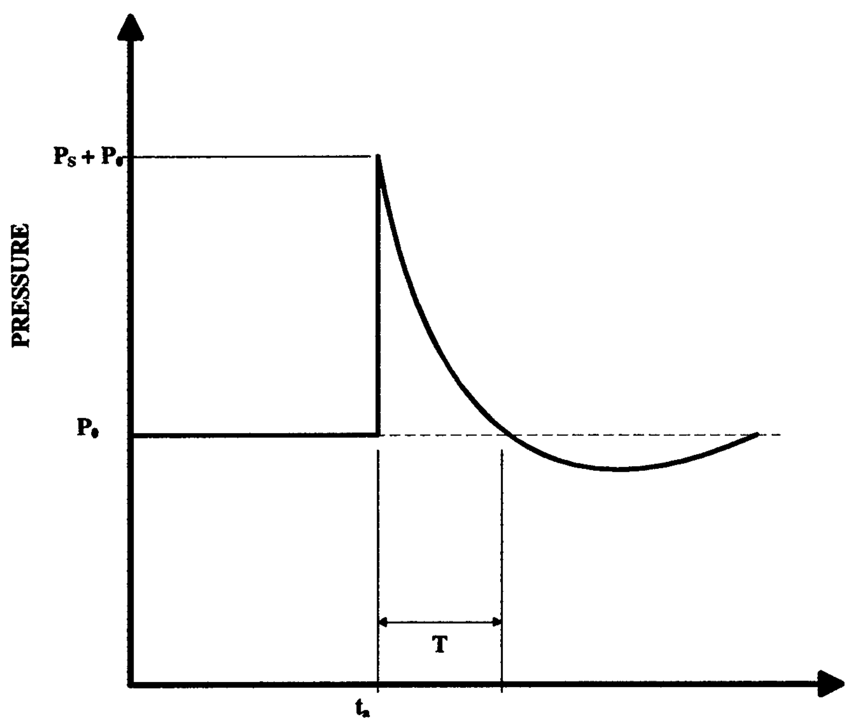


Figure 4. Typical explosive pressure wave in air is plotted versus time.

overmatched engagement. The next two layers are designed to act as a self-sealing bladder, to stop gases from leaking out the impact entrance hole. The fourth layer is a blast absorption layer consisting of rigid porous foam, which will absorb the blast energy from any detonated stowed rounds. Finally, the exterior layer is the pressure retention layer which will contain the internally generated pressures without rupturing for a period of time long enough to allow for the venting system to operate. The venting system used in this design is a burst open vent grid. The overpressure and toxic gases generated during an encounter will be quickly vented to the exterior of the vehicle.

III. Ammunition Analysis

Information on the expected ammunition to be used in this vehicle was obtained from NSWC-Dahlgren. The information we obtained was the data submitted to obtain an Interim Hazard Classification (IHC) for the ammunition. Information is currently available for two (2) HEI rounds, two (2) TP-T rounds, an MPLD round, and one APFSDS round. It is undersood that there is one other HEI round under consideration for use with this system. The supplier and the pertinent information about each round is presented in Table 1. There are two separate storage and feed systems for the APFSDS and HEI rounds. The worst case scenario were selected to conduct our analysis of the pressures generated by an over-matched threats. This would be an engagement that produces the most gas, hence the round that contains the most energetic material.

Currently the HE round with the most energetic material is the EX 238 round with 150 grams of propellant and 151 grams of high explosive, as shown in Table 1. The APFSDS round has 184 grams of propellant, the largest propellant mass. The propellants used in the rounds are Nitocellulose based. The high explosive used in the rounds is PBXN-5 (95.5% HMX, 4.5% Estane). The following table summarizes the energetic material properties of interest in this program:

Property	HMX	NC
Density (g/cc)	1.89	1.659 (Nominal 1.50)
Pcj (kbar)	390	210
Detonation Velocity (km/s)	9.11	7.30
Detonation Energy (MJ/kg)	6.395	4.04
Heat of Formation (kcal/mol)	+17.93	-191 (- means exothermic)
Heat of Detonation (kcal/g)	1.62	1.95 (H_2O (l))
Heat of Detonation (kcal/g)	1.48	1.02 (H_2O (g))
Specific Heat (C_P) (cal/g-C)	0.231	0.370
Gamma	2.740	3.21 (Calculated)

In the analysis of gas generation, we assumed all of the energetic mass was either HMX or NC.

Table 1. Ammunition analysis for AAAV 30mm gun.

Supplier	Description	Type	Part Number	Propellant (grams)	Explosive (grams)	Total Energetic Material (grams)
Alliant	30mm Cartridge, High-Explosive Incendiary	HEI	28068067	RP-1315 (147)		(201.75)
Alliant	30mm Projectile, High-Explosive Incendiary	HEI	28068070		PBXN-5 (48)	(53.4)
Alliant	30mm Cartridge, Test Projectile-Traced	TP-T	28068069	RP-1315 (147)		(149.95)
Raufoss	30mm x 173 Cartridge, Multi-Purpose Low Drag-Tracer	MPLD		PC 5207 WIMMIS (160)	PBXN-5 (18)	(197)
Raufoss	30mm x 173 Cartridge, Armor Piercing Fin Stabilized Discarding Sabot	APFSDS		PC 5207 WIMMIS (184)		(185.8)
Primex	EX 238 Mod. 0, 30mm x 173 Cartridge, High-Explosive Incendiary - Tracer	HEI-T		HC-25-FS Hercules (150)	PBXN-5 (151)	(307.23)
Primex	EX 239 mod. 0, 30mm x 173 Cartridge, Test Projectile -Tracer	TP-T		HC-25-FS Hercules (150)		(152.88)

IV. Overmatched Pressure Generation

There will be three (3) different phases in the pressure pulse within the ammunition box when an overmatched threat causes a reaction of the stowed munition. The first phase will be a shock wave generated by the detonation of the munitions. This will be followed by a rapidly moving gas bubble, which will increase the internal pressure in the ammunition box. Then a gradual decrease in the pressure occurs as the gas is vented from the ammunition box to the outside of the vehicle. Each phase of the pressure pulse has been analyzed and design concepts to contain the pressure have been developed.

The pressure generated by an overmatched encounter will depend on the number of munitions that react during an event. This event is statistical in nature and must be determined by the overmatched threat, shot line, and the sensitivity of the ammunition. A shot-line analysis was performed to determine the number of munitions encountered for frontal 60 degree arc engagements. However, the sympathetic detonation tests, which are also needed for this analysis, have not been conducted. Some assumptions were made about the sympathetic detonation of munitions to conclude the analytical effort. It was assumed that three munitions along the shot-line would detonate with an additional three sympathetically detonating, for a total of six munitions reacting to generate the internal pressure.

Both a dynamic and quasi-static pressure loading will be experienced by the containment system. The dynamic pressure loading will be a short duration pulse caused by the shock wave of the detonating explosive or propellant. This pressure will depend on the explosive mass and distance from the initiation. The interior armor system must be designed to withstand this pressure and stop any fragments that are produced by the explosion. The quasi-static pressure loading would be a relatively longer duration, lower magnitude pressure that must be contained and vented.

IV.a Dynamic Loading

The shock wave has the highest pressure and is the most destructive impulse of all the phases. This is a very short duration pulse, which will be localized around the detonating munitions. A typical explosive pressure wave in air is plotted versus time in Figure 4. The velocity of the pressure wave is supersonic, and hence the wave is actually a shock front. Prior to shock front arrival, the pressure is the ambient air pressure, P_0. Upon shock arrival, time of t_a, the pressure increases abruptly to a peak value of $P_s + P_0$. The pressure then decays to ambient in total time $t_a + T$. The pressure continues to decrease below the ambient level, forming a partial vacuum of amplitude P_s^-, and eventually returns to P_0. The portion of the time history above initial ambient pressure is called the positive phase of duration T.[1]

1 Baker, W.E. *et al*, Explosion Hazards and Evaluation, Elsevier Scientific Publishing Co., 1983, pp. 111-112.

In general, two (2) parameters are used to characterize the ability of the blast wave to do structural damage. These two (2) parameters are the peak over pressure P_s and the total positive impulse of the pressure wave. The impulse is the integral of the positive phase of the pressure wave with respect to time. Therefore, the magnitude of the impulse is directly related to the duration of the positive phase of the pressure pulse. The peak over-pressure produced by a charge is a function of the explosive type, explosive mass, and the distance from the charge. The relationship between over-pressure and the charge mass and standoff distance follows the Hopkinson-Cranz or "cube-root" scaling law. This law can be expressed using a dimensional parameter, $Z=R/M^{1/3}$, where Z is the scaled distance, R is the standoff, and M is the charge mass. The significance of the scaled distance Z is that the peak over-pressure is a function of Z only, for charges of similar explosive type and confinement.

The worst case peak over-pressure will occur when a High-Explosive (HE) warhead ignites in very close proximity to the ammunition box wall. The peak pressure generated by this explosion is the PCJ pressure for the PBXN-5 explosive, which is 375 kbar (5440 ksi). This pressure is well above the strength of any material and therefore force can not be contained but must be absorbed. The inner armor/composite layer and energy-absorbing crushable foam will be used to absorb this energy. Hydrocode simulations were used to calculate this shock wave dynamics and the effect on the inner layers of the ammunition box.

IV.b Quasi-Static Pressure Loading

The second pressure loading is the longer duration, quasi-static pressure that must be contained and vented. To determine the final quasi-static pressure immediately after the event has occurred and before cooling of the gas products, Amagat's law and the ideal gas law under adiabatic expansion were used. Amagat's law states: "The total volume of a mixture of gases is equal to the sum of the volumes that would be occupied by the various components each at the pressure and temperature of the mixture." Using the ideal gas law under adiabatic expansion (PV^γ = Constant), where gamma (γ) ranges from 2.5 to 3.5 for explosive products and gamma is 1.4 for air. The gamma used for all the propellant and explosive products was 2.74. Substituting the ideal gas law into Amagat's law yields the following relationship:

$$V_i = [(P_{atm}(V_i)^\gamma/P)^{1/\gamma}]_{air} + [(P_{CJ}(\text{Mass/density})^\gamma/P)^{1/\gamma}]_{exp} + [(P_{CJ}(\text{Mass/density})^\gamma/P)^{1/\gamma}]_{prop.}$$

Where V_i = initial volume of air. This equation was numerically solved for P, the final pressure in the container. This calculation gives an approximate pressure that can be used for the design effort. The results of this analysis are presented in Table 2.

Table 2. Quasi-static pressure in ammunition system.

Number of reacting munitions		Pressure (psi) above ambient	
Exp.	Prop.	No stowed rounds	Box full of stowed rounds
1	1	1.4112	7.0707
3	3	4.6599	47.6868
6	6	10.7163	202.5072
0	6	4.9245	52.0968
0	3	2.2932	15.1851
0	1	0.7203	1.8963

Cases of one, three, and six rounds reacting were evaluated. If it was an HE round then there would be explosive and propellant present in the calculation and if the round was an AP round only propellant would be used in the calculation. There are also two extremes for the initial air volume in the ammunition system. The largest initial air volume is when there are no rounds in the box except the ones reacting. The smallest initial air volume is when the box is completely full of stowed rounds. Any storage situation between these two extremes is possible. A pressure of 200 psi was selected for the maximum quasi-static over-pressure based on these calculations. Applying a 1.50 factor of safety, the design pressure used for the analysis of the outer pressure wall design was 300 psi.

IV.c Venting Dynamics

The final phase of the pressure pulse is the venting of the gases out of the ammunition system. The standard formula for mass flow rate through a constriction (orifice) was used for this calculation. This formula is:

$$\dot{m}_{out} = \rho \, C_Q \, (\pi d^2 / 4) \sqrt{(2 \Delta p / \rho)} \, / \, (1 - (d/D)^4)$$

where d is the orifice diameter, D is larger pipe diameter, and Δp is the pressure difference across the orifice. If diameter D of the pipe (or container) is significantly larger than the diameter d of the orifice, then this reduces to:

$$\dot{m}_{out} = \rho \, C_Q \, (\pi d^2 / 4) \sqrt{(2 \Delta p / \rho)}$$

For large Reynolds number, the coefficient C_Q quickly approaches the value of 0.6. The Reynolds number is expected to be large because the flow velocity should be large and the viscosity of the gases is very low.

The munitions are sources of the product gases over the period that they are reacting or burning. Burning occurs very quickly (a few hundred microseconds). It can be assumed to be instantaneous. Then this may be described mathematically as:

$$m^{\cdot}_{in} = M_{exp} / T_{burn}\ , \text{ for } t < T_{burn}$$
$$m^{\cdot}_{in} = 0\ \ , \text{ for } t < T_{burn}$$

Where M_{expl} is the total mass of energetic materials burned. Assembling these two terms yield the total mass rate in the container as:

$$m^{\cdot} = m^{\cdot}_{in} + m^{\cdot}_{out}$$

This equation is easily numerically integrated to find the mass *m* of gas in the container at any time. Its pressure may then be determined by assuming an adiabatic expansion of all gas products. The pressure inside the container at any time is give by:

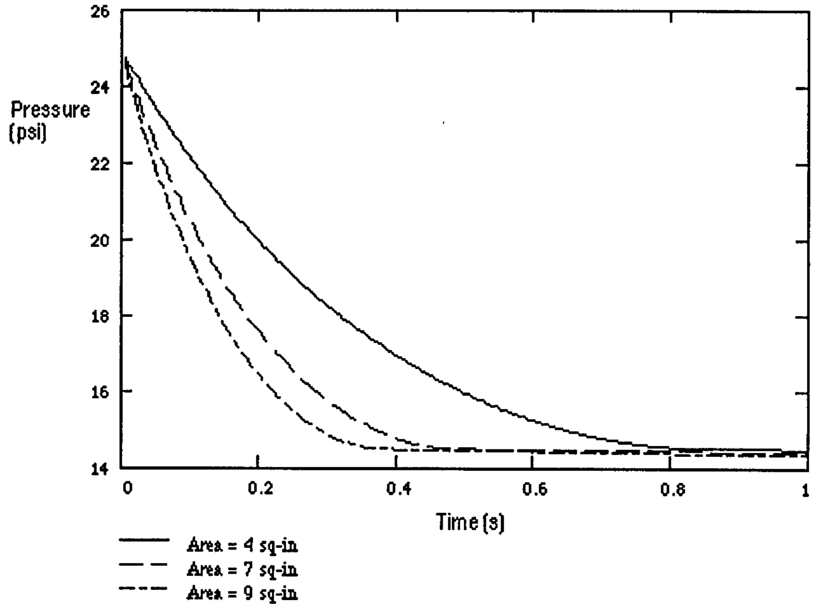
$$[\,(p / p_a)^{1/\gamma a} / V + (P_{0,e} / P)^{1/\gamma e} (N_e m_e / \rho_{0,e}) + (P_{0,p} / P)^{1/\gamma p} (N_p m_p / \rho_{0,p})\,]$$
$$(m / m_0) = V + (N_e m_e / \rho_{0,e}) + (N_p m_p / \rho_{0,p})$$

Where ρ_0 is the initial mass density, γ is the ratio of specific heats, and the subscripts a, e, and p refer to air, explosive, and propellant, respectively. The last two terms on the right-hand side account for the additional volume contributed by the reacted charges. This equation must be solved numerically for the pressure p as a function of the current mass m within the container.

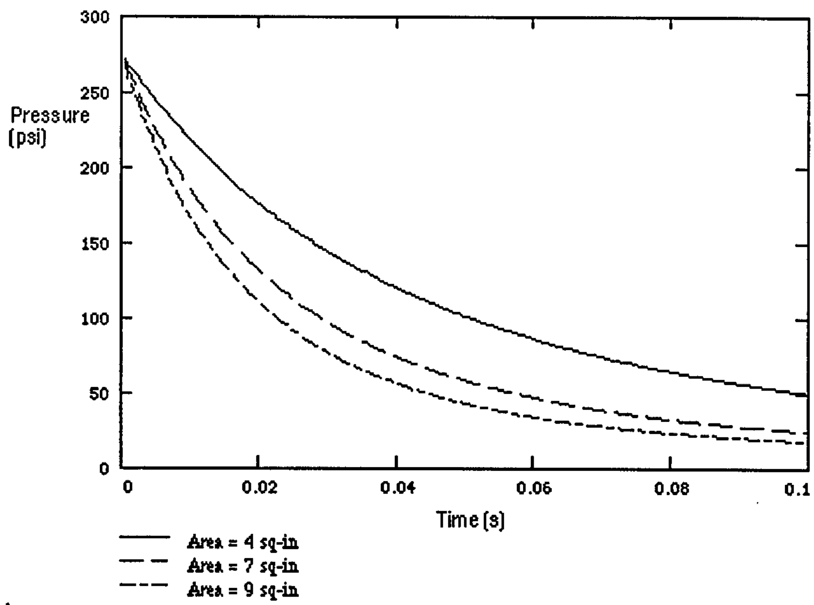
The calculation results are shown in Figure 5. Three vent areas were considered and the pressure plotted as absolute pressure, 14.7 psi, is atmospheric conditions. Six HE munitions reacting was the only case considered. In the first case, shown in Figure 5a, the ammunition box with no stowed rounds, only the six rounds that reacted were in the system. This is the case where the largest volume of air is present. The results for the ammunition box completely full of stowed rounds is presented in Figure 5b. Here the minimum volume of air is present in the system. Based on this analysis it appears seven square inches of venting area will reduce the pressure within the ammunition system in approximately 0.1 seconds after the vents burst open.

V. Venting System

The venting system design is a burst-open vent grid that would be mounted on the underside of the turret. An area on the turret directly beneath the gun feed enclosure was identified for this vent grid. The feed system comes very close to the turret walls here and lends itself well to venting at this location. Analyses were performed to determine the sizing of the vent grid and the material to be used.



a.) No stowed rounds.



b.) Full of stowed rounds.

Figure 5. Dynamic venting of internally generated pressure for three vent areas.

V.a Grid Sizing

The venting area just under the gun feed system is 14 inches long and 5 inches wide with the inner arc, having a radius of 27 inches, running between the two corners. This does not provide much area to vent the gases. A geometric analysis was conducted to determine how many vent opening could be placed in this area. Figure 6 shows the four venting configurations investigated. The first option has five one-inch diameter holes giving a total vent area of four square inches. The second option has nine one-inch diameter holes in the same area which provides seven square inches of venting. The third option has a 1.0 inch hole, a 1.5 inch hole, and a 3.0 inch hole which produces 9.6 square inches of venting. The fourth option has four 1.5 inch diameter holes giving a total vent area of 7 square inches.

Once the solid modeling effort, discussed later in this report, was complete it was determined that the area for the vent grid could be extended past the ammunition feed system. The final location of the vent holes on the turret shelf is shown in Figure 7. Three-inch vent holes have been selected to maximize the area of the hole for material shearing and venting reasons. Figure 7 shows four vent holes but from our previous venting calculations it was shown the minimum vent area required is 7 square inches. Each three-inch diameter hole represents 7 square inches of vent area. It is recommended that a minimum of two vent holes be used. Additional vent area would reduce the time the over-pressure is experienced but may weaken the turret structure. Again, loading and strength requirements would be required from the vehicle manufacture to determine if the design still meets the turret structural requirements. The venting area can be structurally reinforced around the vent holes to compensate for any lost strength.

V.b Material Failure Analysis

As previously discussed, a quasi-static overpressure of 200 psi was established from the analysis of the overmatched pressure generation. This represents the amount of gas generated by six HE rounds. Based on this result, the vent system was designed to burst at an internal pressure of 200 psi. Since the dynamic blast loading will produce pressures well above 200 psi for very short time duration, this vent burst pressure is considered to provide a built-in safety factor.

To burst a vent hole open the vent material must shear under the 200 psi pressure. Estimations of the vent material shear strength for circular vent holes and a 200 psi over pressure were performed. The results of this evaluation are presented in Figure 8. Table 3 is a summary of candidate vent materials and shear strengths :

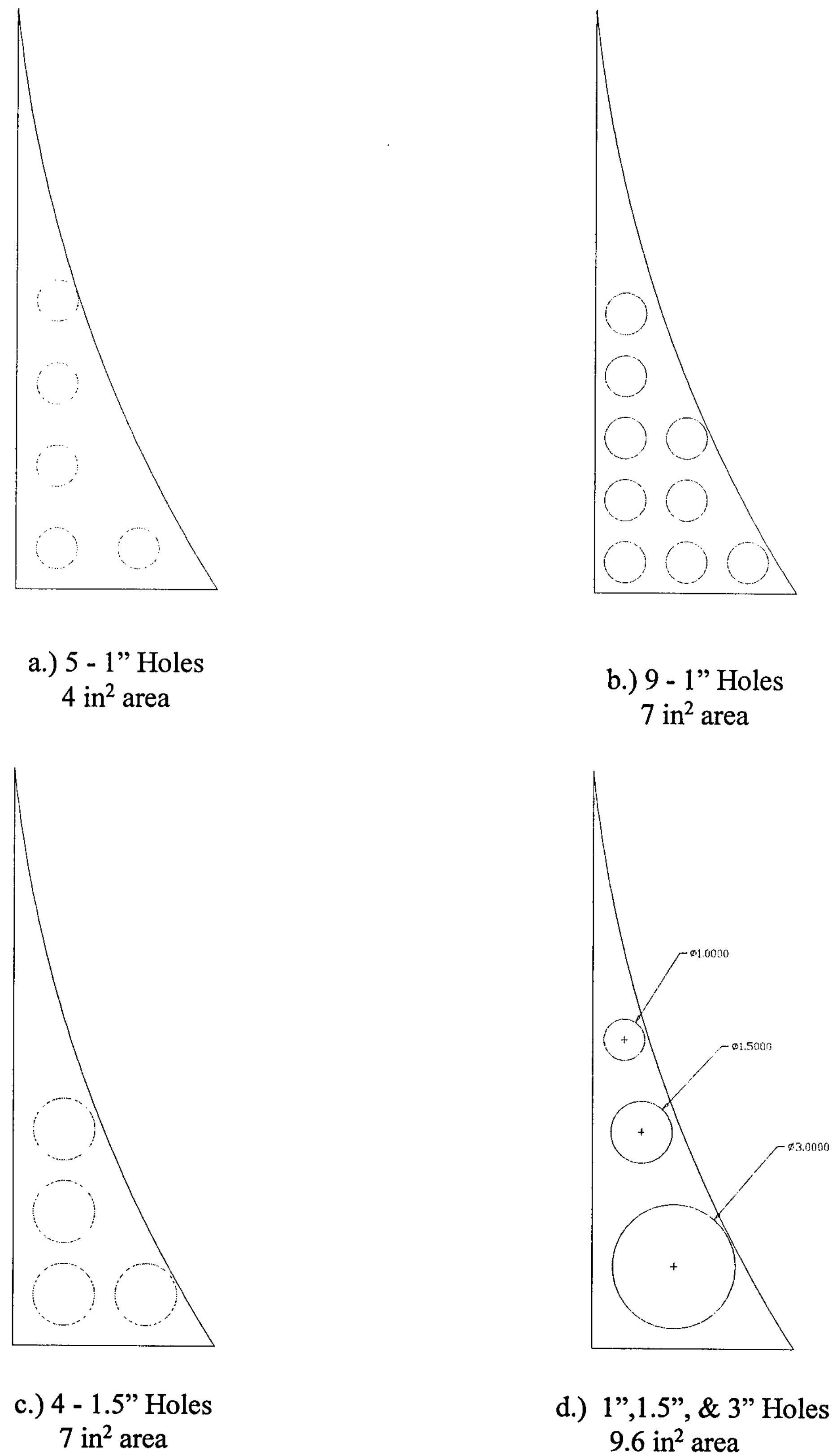


Figure 6. Initial four venting configurations investigated.

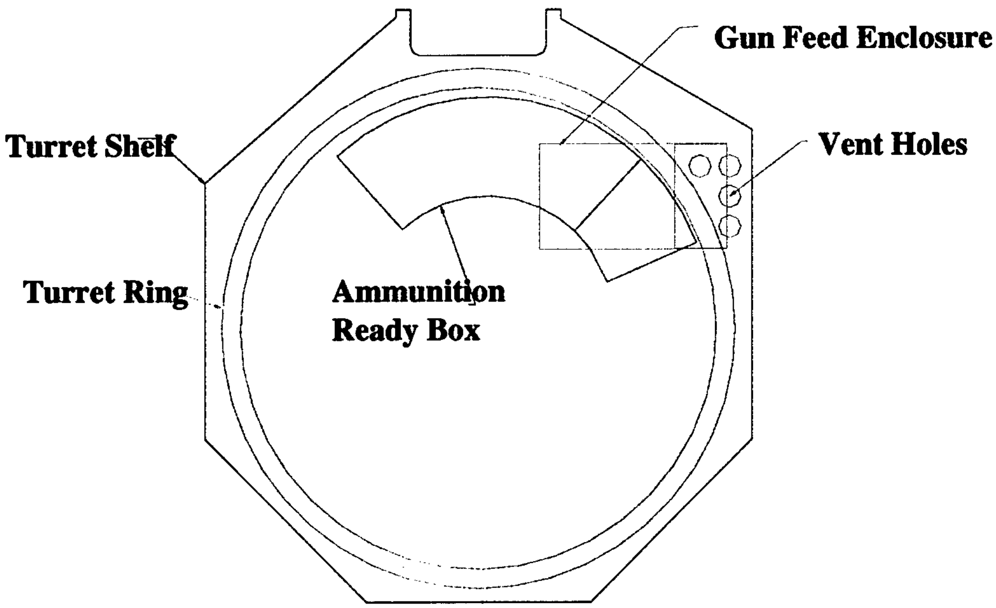


Figure 7. Final vent hole configuration shown on full view of turret shelf.

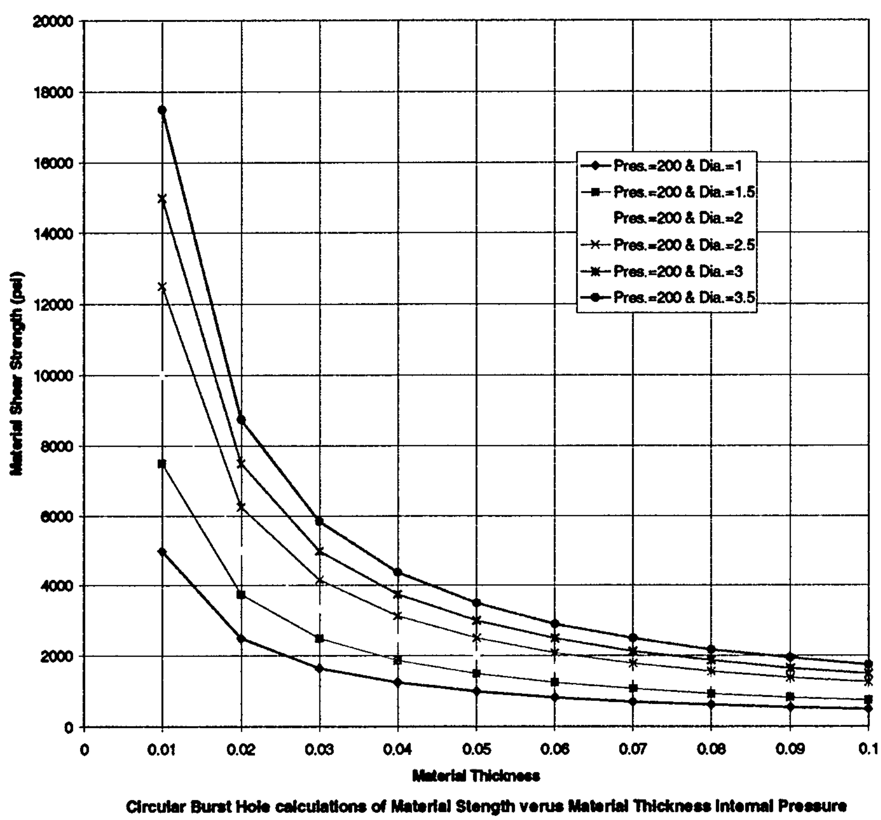


Figure 8. Estimations of the vent material shear strength for circular vent holes and a 200 psi over pressure.

Table 3. Vent material shear strengths.

Material	Shear Strength (ksi)
Epoxy	14.0
Polyester	21.4
Vinylester	22.7
1060-O Aluminum	7.0
1100-O Aluminum	9.0
2024-O Aluminum	18.0
2024-T4 Aluminum	41.0
5083-O Aluminum	25.0
6061-O Aluminum	12.0
6061-T6 Aluminum	30.0

Materials with low shear strengths were selected for this application. Selecting 1060-O or 1100-O aluminum as the burst material, a two (2) inch diameter vent hole with 0.018" web thickness or a three (3) inch diameter vent hole with a 0.022" web thickness will burst at 200 psi internal loading. If Epoxy or 6061-O aluminum were selected as the burst material a three (3) inch diameter hole with a 0.012" web thickness. These examples are given to show how the analysis was used in the final design process. The loading environment which the vent structure must survive must be the second step in the design process to select a final configuration. Also, using the vent analysis discussed, a minimum vent area of seven (7) square-inches should be used to provide the required venting.

Aluminum was determined to be the best material to select for this application. Initial investigations suggested 6061-O with a web thickness of 0.012-inches would be the best material to select. The exact vent grid material will require input from the vehicle manufacturer, such as environmental constraints and loading conditions on the turret.

VI. Ammunition Container System

The design approach for the ammunition containment system was to use a multi-layer, pressure vessel wall configuration. The wall configuration is designed to contain internal pressure and absorb the energy associated with the blast wave and fragmentation from internally detonated rounds. The design of this wall was divided into two tasks, armor design and pressure containment. The armor design effort focused on fragment protection and energy absorption. The pressure containment effort focused on the selection of materials and composite lay-up required to contain the quasi-static pressure loading.

The current ammunition containment system geometry and wall configuration is presented in Figure 9. The innermost layer is armor steel designed to stop all internally generated fragments from the reaction of the stowed munitions. An elastomeric seal

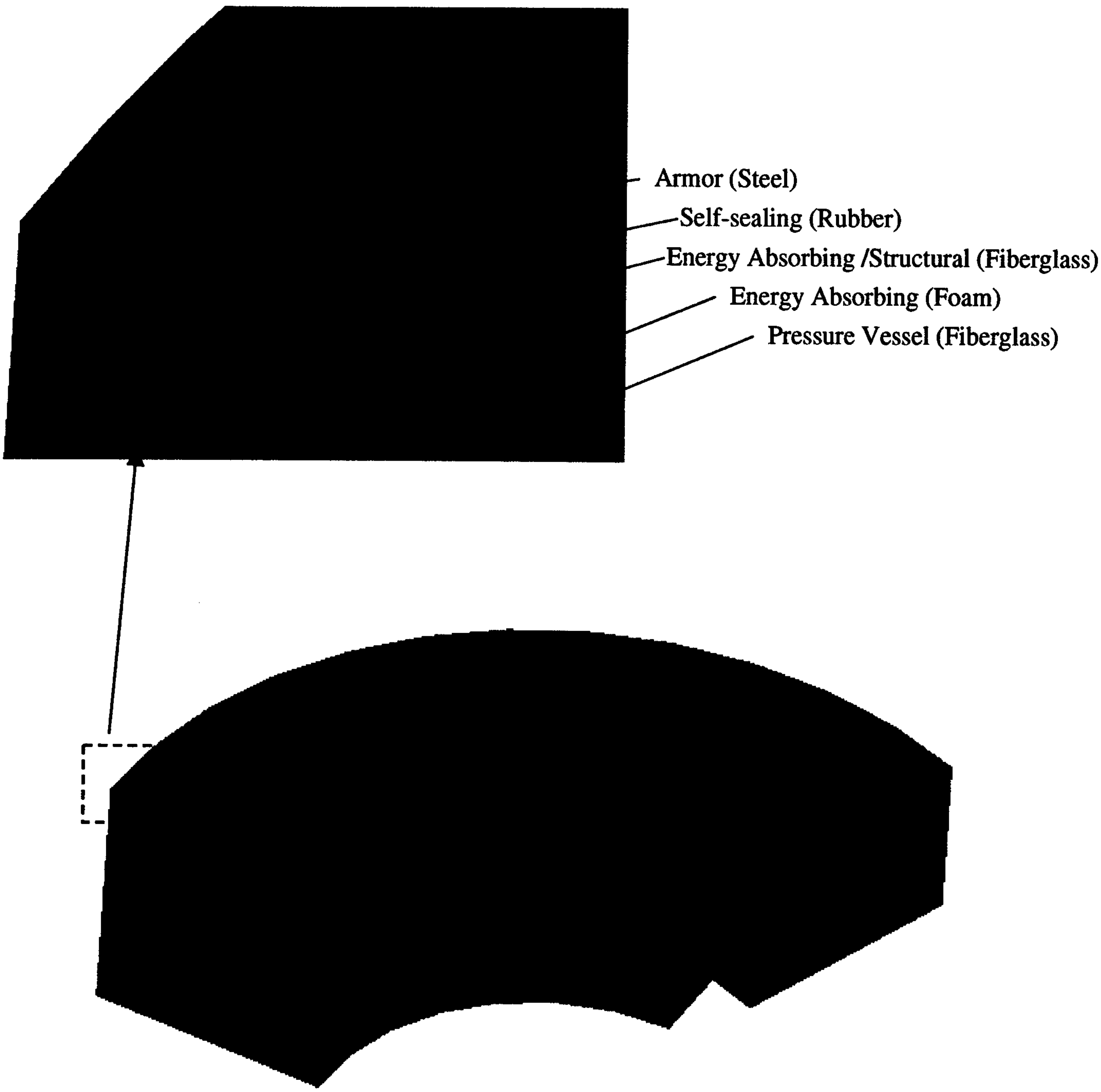


Figure 9. The current ammunition containment system geometry and wall configuration.

layer of EPDM rubber is the next layer intended to provide the sealing of the entrance hole to prevent leakage of the internal gases. A quasi-isotropic fiberglass/epoxy composite as the next layer provides structural confinement for the elastomeric rubber and also distributes the blast loading over a larger area. This is followed by a crushable foam layer, which is designed to absorb the blast and impact energy. Finally, the outer layer is a quasi-isotropic fiberglass/epoxy composite designed to contain the internal gas pressure prior to venting.

VI.a Armor Layer Analysis

An analysis was performed to determine the thickness of steel required to stop the internally generated fragments produced when a stowed munition detonates within the containment system. The mass, size, and velocity of the fragments are required to conduct this analysis.

Fragment size and velocity data was obtained from the arena test data for the HE ammunition. The data was reported as average fragment weight and velocity for each round as shown in Table 4. The minimum mass fragment measured was 0.5 grains. A range of fragment weights would also be very useful data for the armor design analysis. It was assumed that multiple fragment impacts would occur in close proximity to each other. This would produce more damage to the armor layer requiring a robust material and thickness. The means of estimating a multiple fragment impact event was to investigate fragments which have a large impact surface area in the analysis.

Table 4. Fragment summary from arena tests for HE ammunition.

Weapon ID	Average Velocity (ft/s)	Average Fragment Weight (grains)	Total Number of Fragments
AF	3122.4	14.2	287.8
P	2474.1	7.1	539.0
A	2452.0	5.9	545.6
R	2195.4	75.4	43.9
N11	2944.8	3.72	298.3

Design guidelines for the inner steel layer were generated using the armor design handbook, entitled "Ballistic Technology of Lightweight Armor - 1981." In this reference, curves of armor areal density versus protection (V_{50}) ballistic limit are presented for a given projectile/armor combination. Protection (V_{50}) ballistic limit is the velocity at which 50 percent of the bullets will be stopped by the armor. There are curves for various impact angles or obliquity. The projectiles of interest for this program are the projectiles most closely matching the mass and velocity of the fragments defined above.

They are categorized as follows:

Cal. 0.10	1.35 grains
Cal. 0.15	5.86 grains
Cal. 0.22	17.0 grains
Cal. 0.30	44.0 grains
Cal. 0.45	147.0 grains
Cal. 0.50	207.0 grains.

The average fragment was defined using the HE ammunition casing. The velocity of the HE ammunition casing is 1.03 km/s or 3380 ft/s and the casing thickness varies from 5 to 6 mm along the length. Assuming a cubic fragment with an equal length to thickness ratio (a 5mm cubic fragment) for the casing fragments results in an average fragment mass of 15 grains.

Data for all steel targets was reviewed and it was determined that the curves for 300 BHN hardness steel were the most appropriate set of data to use for this analysis. This steel is also very similar to what we would recommend in the construction of the armor box. Data was available for three mass fragments (830, 207, and 44 grains). Being conservative the 44 grain curve simulating the mass of three average fragments at a 3400 fps velocity was selected. An RHA Steel (300 BHN) plate of 10.4 psf is required to stop this fragment. This translates to 0.25 inches of steel at normal impact.

Based on a quarter inch thick steel armor plate, the ballistic limit velocity (V_{50}) for each fragment simulant was taken from the handbook. This data is plotted with the fragment data for the HE ammunition in Figure 10. Any point below the curve will not penetrate the quarter inch armor plate. As can be seen all the average fragments lie below the curve. If further detail on the fragments generated by the HE munition was available a range fragments could be presented on this plot.

This analysis would be conducted again for a thinner plate until the HE munition fragments lie above the curve then the minimum thickness would be identified. Since the exact range of fragments the rounds produce is not known, a 0.25 inches thick plate is recommended as a *minimum* thickness for the armor plate. This thickness is also recommended since the armor plate is expected to experience multiple impacts.

VI.b Energy Absorption Layer Analysis

The CTH hydrocode was used to design the thickness and density of the energy absorbing foam layer. Axisymmetric simulations were conducted using three fragment geometries impacting the wall configuration at 1.03 km/s. The geometries were steel cylinders with a thickness of 5mm and diameters of 10, 20, and 30mm. The weight of these fragments is 47.4, 189.6, and 426.7 grains. The initial material plot for this simulation is shown in Figure 11. The foam material was modeled as a crushable

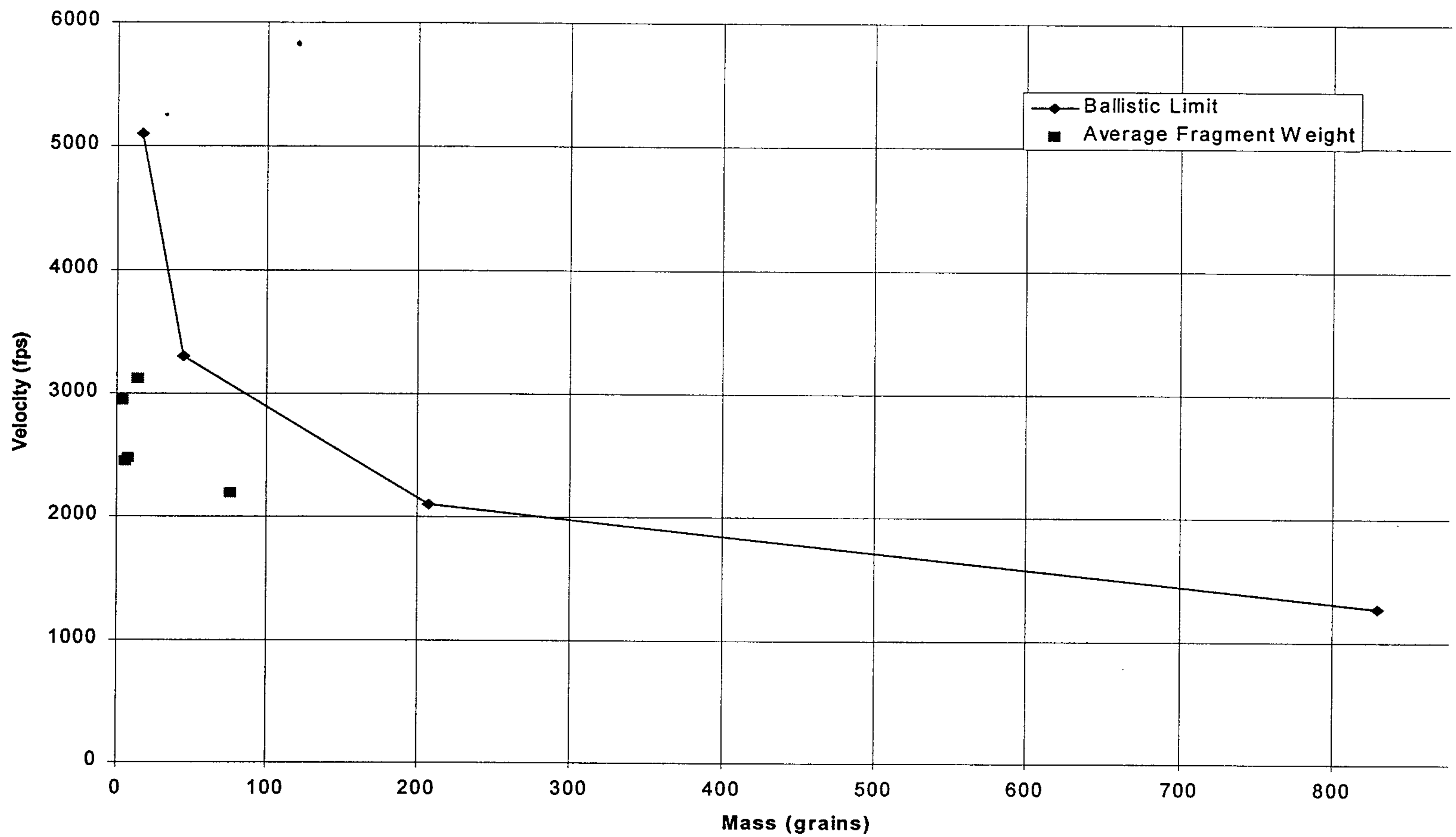
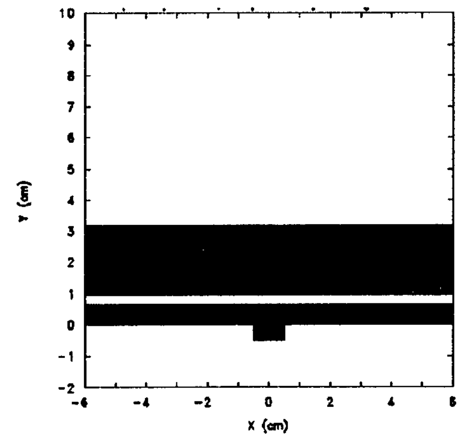
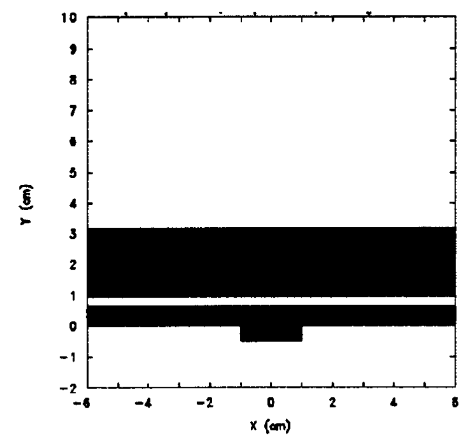


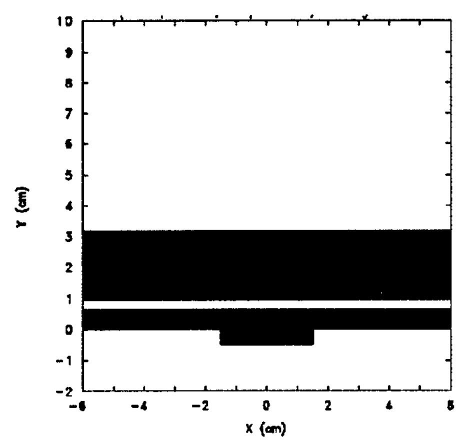
Figure 10. Ammunition High-Explosive (HE) fragment data versus armor ballistic limit data..



a.) 10mm diameter fragment (47.4 grains)



b.) 20mm diameter fragment (189.6 grains)



c.) 30mm diameter fragment (426.7 grains)

Figure 11. The initial material plot for crushable foam material simulation is shown.

material using a p-alpha porous material model. Three different wall configurations were also evaluated. The baseline wall construction was:

0.250 inch steel
0.125 inch rubber
0.125 inch glass composite
0.500 inch foam, 20 Pounds-per-Cubic-Foot (pcf) density
0.250 inch glass composite.

The two variations on the baseline wall configuration included a thickness change to 0.25-inches keeping the 20pcf density, and a density change to 10 (pcf) keeping the thickness at 0.50-inches. Simulation material plots for the baseline wall configuration at 60 us after impact are shown in Figure 12.

The objective of this analysis was to determine the required thickness and density of the crushable foam to minimize impact loading on the outer composite wall. As can be seen in these simulations the 0.25-inch thick armor plate can stop the 10mm diameter fragment (47 grains) with minimum damage and even arrest the 20mm diameter fragment (189 grains) with minor fracture to the armor wall. The 0.5-inch thick 20pcf foam was selected for the design since the simulations showed the best load transfer and energy absorption characteristics. The 0.25-inch thick foam did not absorb the energy as effectively and the simulation of the 20mm fragment showed larger deflections in the rear composite plate. The 10pcf foam crushed quicker and did not provide support to other elements in the wall.

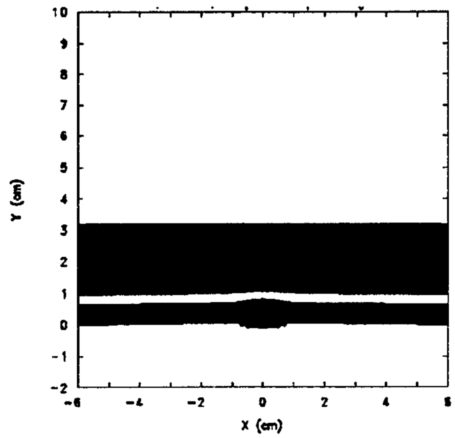
VI.c Pressure Containment Wall Design Approach

The primary function of the pressure containment system is to contain and prevent leakage of internal gases into the crew space after an overmatching threat. The pressure vessel wall must be designed to contain the internal pressure without rupture long enough for the venting system to operate. This requires that the pressure retention wall consist of a high strength, energy absorbing material system. Sealing capability is provided with an elastomeric inner layer. To allow deformation of the composite pressure vessel resulting from internal pressure, an air gap or elastomeric outer material layer is located on the exterior face of the composite pressure vessel.

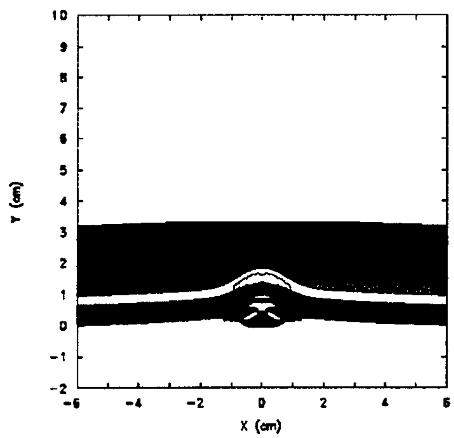
The Phase I design development and evaluation process for the composite pressure containment wall consisted of the following main elements:

1. Identification of candidate material systems and selection of initial case-wall material lay-up.

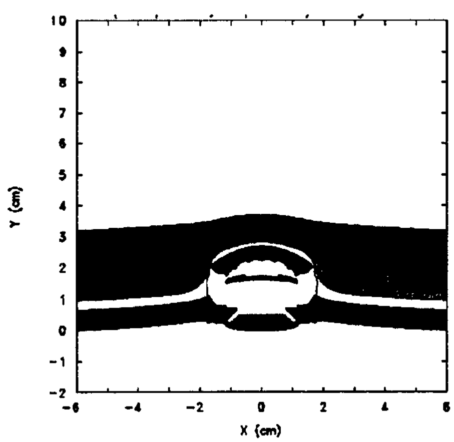
2. Identification of a "representative" quasi-static pressure loading condition.



a.) 10mm diameter fragment (47.4 grains)



b.) 20mm diameter fragment (189.6 grains)



c.) 30mm diameter fragment (426.7 grains)

Figure 12.. Simulation material plots for the baseline wall configuration at 60 us after impact.

3. Parametric study using composite laminate plate theory software to establish initial case wall lay-up and thickness required to contain pressure.

4. Development of containment system geometry (including ammunition can, feed rail assembly and gun feed containment system) from available design drawings. Engineering of structural support frame, access doors and attachments.

5. Finite element stress analyses of HE ammunition container, lid and support frame using ANSYS FEA code.

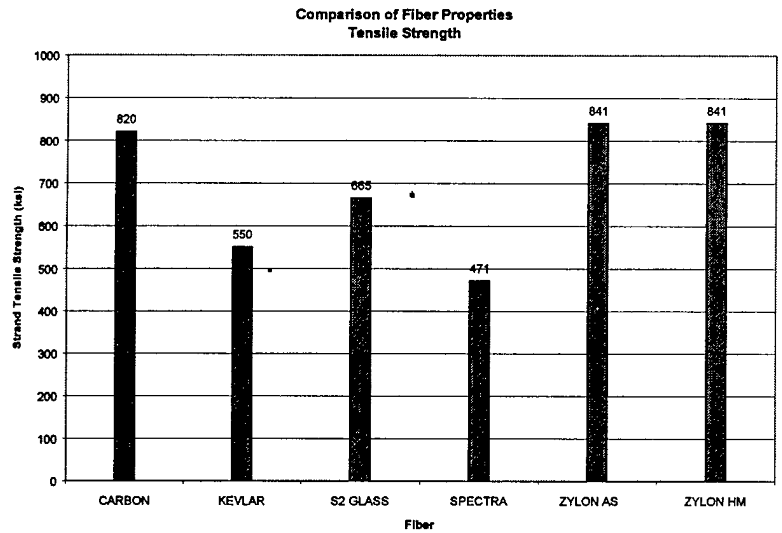
6. Generation of 3-D solid models of containment system geometry.

VI.c.1 Composite Material Trade Study

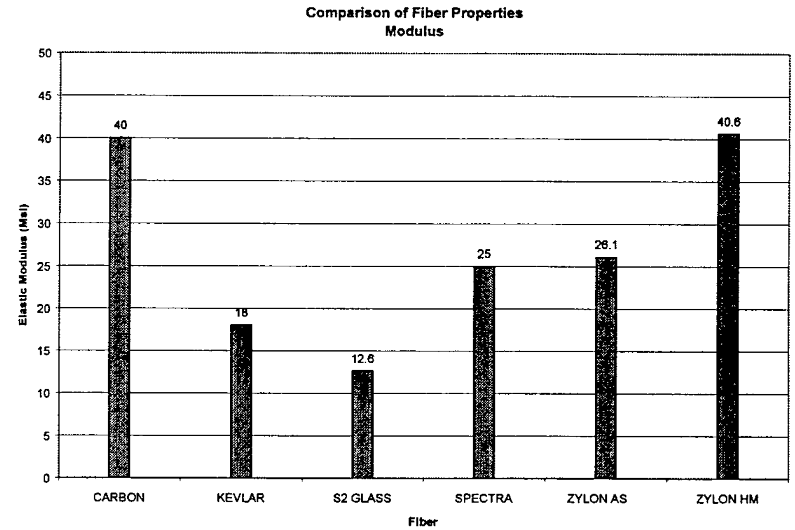
Several candidate fiber and resin materials were identified as part of the initial trade study for the pressure containment system. Candidate fiber materials that are being considered include: carbon, glass, aramid (Kevlar), oriented polyethylene (Spectra) and liquid crystal polymer (i.e., Zylon® polybenzoxazole (PBO) fiber). Candidate resin materials include polyesters, vinylesters, epoxies, phenolics and urethanes.

In order to meet the multi-functional requirements of structural integrity/durability, ballistic protection, energy absorption, low permeability, and low flammability/toxicity characteristics, a hybrid material system incorporating a combination of different fiber/resin systems would provide the most efficient pressure containment capability. For example, an S-2 glass/epoxy or S-2 glass/thermoplastic layer would provide structural rigidity and ballistic protection while a thin layer of S-2 glass/phenolic would provide flammability/toxicity benefits. Although carbon fiber-reinforced composites are typically used in lightweight pressure vessel applications to provide improved strength compared to other candidate fiber systems, there are concerns over toxicity and electrical conductivity in a AAAV ammunition containment application. In addition to S-2 glass fiber-reinforced material systems, additional materials that were evaluated include Kevlar and Zylon® fiber reinforced epoxies and phenolics. Zylon® is a relatively new PBO ballistic fiber which provides superior tensile strength and modulus compared to p-aramid (Kevlar) fibers. It also has outstanding flame resistance and thermal stability with low moisture regain (0.6%) and dimensional stability against humidity. This fiber has recently shown superior impact performance for engine containment barrier and bullet-proof vest applications.

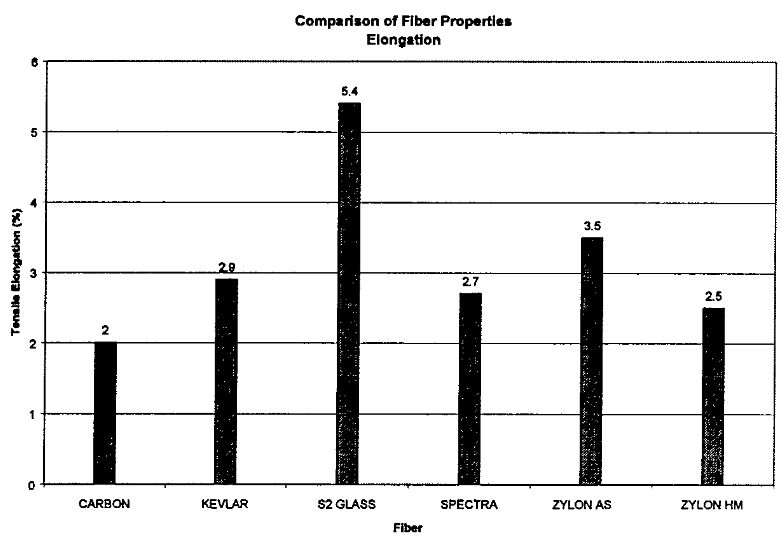
Figure 13 presents a comparison of "average" strengths, modulus, strain-to-failure (elongation) and cost of candidate fibers. Depending on the specific fiber type selected (e.g., T40 vs IM7 carbon) there will be some variation in the properties and/or cost. Carbon fibers, although offering the highest strength/stiffness performance, were eliminated from consideration due to electrical conductivity and toxicity concerns. The



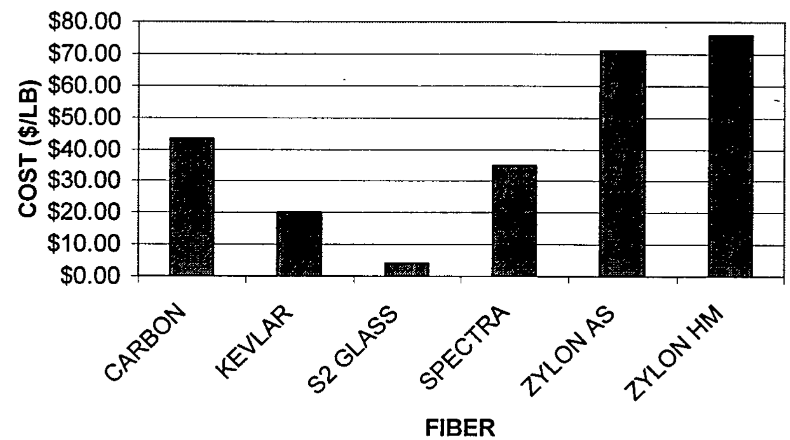
a.) Tensile Strength Comparison.



b.) Elastic Modulus Comparison.



c.) Tensile Elongation Comparison.



d.) Cost Comparison.

Figure 13. Comparison of "average" strengths, modulus, strain-to-failure (elongation) and cost of candidate fibers..

relatively high cost of carbon fiber was also a reason for its elimination from consideration. Among the candidate fibers considered, S2 glass fiber was selected for the composite structural layer reinforcement for the baseline pressure containment wall design because of its higher strength, elongation and lower cost. (S2 glass fiber costs approximately $4/lb, compared to Kevlar at about $20/lb and intermediate modulus carbon fiber at more than $40/lb.) However, the cost of Zylon PBO fiber (more than $70/lb) is significantly higher. Availability, cost, and material property information was also obtained for fabric reinforcements, specifically S2 glass fabrics, since the manufacturing approach for the ammunition containment system would employ a resin transfer molding (RTM) operation using fabric prepreg material.

Several different resin systems were also considered and evaluated as part of the Phase I material trade study. In addition to lower cost polyesters, vinylesters and conventional epoxy and phenolic resins, non-conventional resin systems such as urethanes were also considered to provide multi-functional performance capability. Specific resin systems and processing characteristics are compared in Table 5. Significant requirements for the resin included relatively low viscosity, low toxicity and flammability, compatibility with RTM manufacturing, and previously demonstrated performance in a pressure vessel application. Based on these considerations, Shell Epon 9405 epoxy resin with an Epi-Cure 9470 Curing Agent was selected for the baseline composite pressure wall design.

Consistent with the conservative design approach to use proven materials to provide sufficient armor protection, sealing capability and pressure retention while maintaining relatively low costs, S2 glass/Epon 9405 was selected as the baseline material system for the ammunition containment system design. If it is necessary to provide a multi-functional, energy absorbing, self-sealing pressure wall design to meet specific weight constraints, an advanced material system using S2 glass or Zylon PBO fiber and polyurethane resin could be considered, provided that the urethane resin satisfies the system requirements for low flammability/toxicity. Alternatively, an outer layer of fiber reinforced phenolic could be used to satisfy low flammability requirements. Recent ballistic testing by the U.S. Navy has demonstrated that a high strain-to-failure fiber-reinforced urethane matrix material successfully contained 50 caliber fragments at velocities up to 2100 feet per second with small damage area and no shrapnel created as a result of impact. In addition, the urethane matrix material proved to be virtually self-sealing, with no resulting hole following penetration.

VI.c.2 Composite Material Lay-up

Material property data compiled from the literature, including technical information received from Hexcel Corp. and Owens-Corning Fiberglass Corporation concerning S2/Epoxy fabrics, were used in conjunction with the COMPOSITE PRO v3.0 software program to determine an acceptable lay-up for the HE ammunition storage compartment and lid. A quasi-isotropic, interspersed symmetric lay-up was established to provide sufficient strength for the anticipated multi-axial loading condition resulting

Table 5. Candidate resin system analysis.

Type	Supplier	Designation	Viscosity		Injection Temp		Cure Temp
			RT	@ Elev Temp	Resin	Mold	
Bisphenol A	DOW Chemical	Tactix 123/H41	3200	130@127	125-150	150-200	250-350
	Shell Chemical	Epon 826	6500	450@122F	RT	RT	RT-350
		Epon 9405/ Epi-Cure 9470	850	100@140F	RT-140	200-250	250-350
Toughened Epoxy	3M	PR500	Paste	100@180	230	320	350
Phenolic	BP	Cellobond J2018L	700	----	RT	80-100	140-180
Isophthalic Polyester	Ashland Chemical	AROPOL 7241RT	250	----	77	85	77
Vinyl Ester	DOW Chemical	Derakane 411-350	350	----	RT	100-180	100-180

from an internal pressure load of 300 psi. The lay-up resulting from this analysis was [90/0/±45/90/0/±45]s, as shown in Figure 14. Laminated plate and thin wall cylindrical pressure vessel analysis routines within COMPOSITEPRO were used to predict maximum deflections and stresses. Since the ammunition container and feed system were designed around the current AAAV design envelope, a more efficient cylindrical pressure vessel geometry could not be used. The analyses performed using COMPOSITEPRO provided only an initial approximation of the deflections and stresses to define a lay-up and wall thickness for the finite element analysis of the full-scale AAAV ammunition containment system geometry.

VII. Structural Design and Analysis

The structural design and analysis effort in Phase I focused on the ammunition ready container geometry. The Finite-Element Analysis (FEA) models included the tub, or bottom and side walls of the container; the lid, or removable top of the HE container; and the structural support frame for mounting/attachment of the lids to the tub and the entire containment system to the vehicle. The general design criteria used in the development of a recommended composite pressure containment wall design was to limit the maximum deflection to below 0.5 inches, in order to maintain sealing capability, and limit the maximum composite wall stresses to below the allowable equivalent strength established for S2 Glass/Epoxy (100.1 ksi).

VII.a Finite Element Analysis for Ammunition Ready Container

To evaluate the displacements and stresses for the HE ammunition container geometry, an ANSYS 3-D finite element model was developed. The initial analyses of the baseline lay-up was performed using three-dimensional shell elements to model the HE ammunition box. Multi-layer composite shell elements (ANSYS SHELL 99) were used for this analysis. The loading condition used for the analysis was an internal pressure of 300 psi. The model was constrained to fix the bottom edges of the can. The initial analysis performed for the HE ammunition can was performed to evaluate the deflections and stresses for three different wall thicknesses (i.e., 0.25, 0.375 and 0.5 inches). Figure 15 presents the predicted maximum deflection as a function of the composite wall thickness for the HE container. Representative displacement and fiber direction stress contours for the HE container shell model with a 0.5 inch wall thickness are also shown.

The results of the analyses for the shell parametric model indicated that a S2 Glass/Epoxy wall thickness of 0.5 inches is required to limit the maximum deflection to below 0.5 inches over most of the HE can. Areas of high stress concentration were predicted at the center of the side walls of the can and at the corners, as shown.

Subsequent analyses of the HE container were performed using 3-D solid elements in order to include steel structural support framing to reinforce the composite

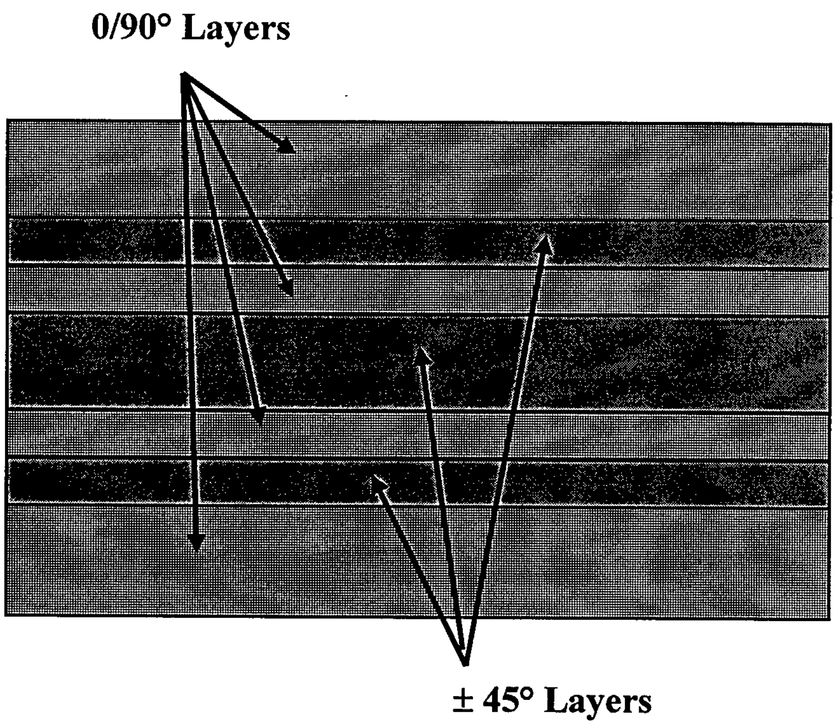


Figure 14. Quasi-isotropic lay-up [90/0/±45/90/0/±45]s resulting from this analysis.

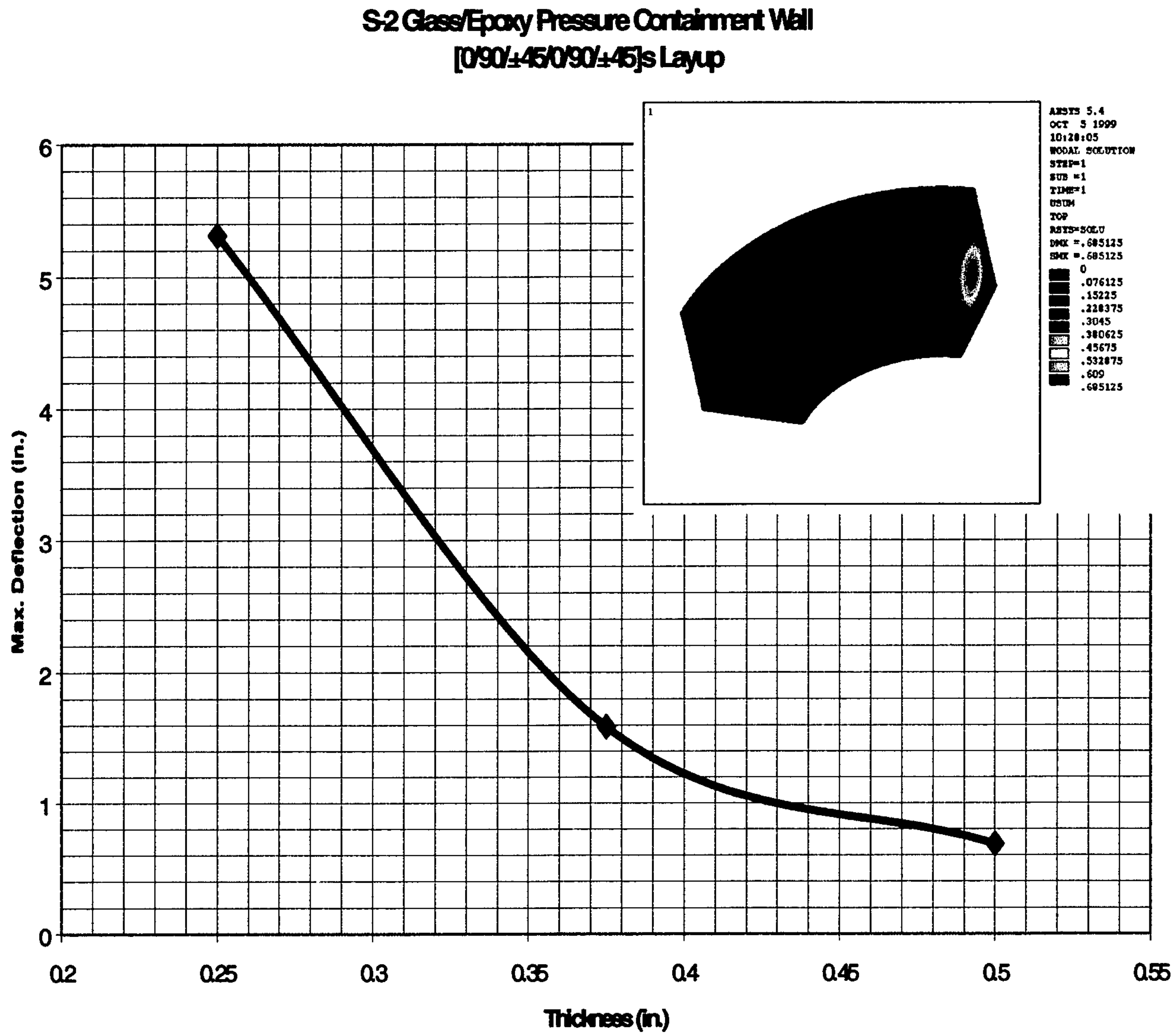


Figure 15. Three-dimensional shell elements model maximum deflection predictions as a function of the composite wall thickness for the HE container.

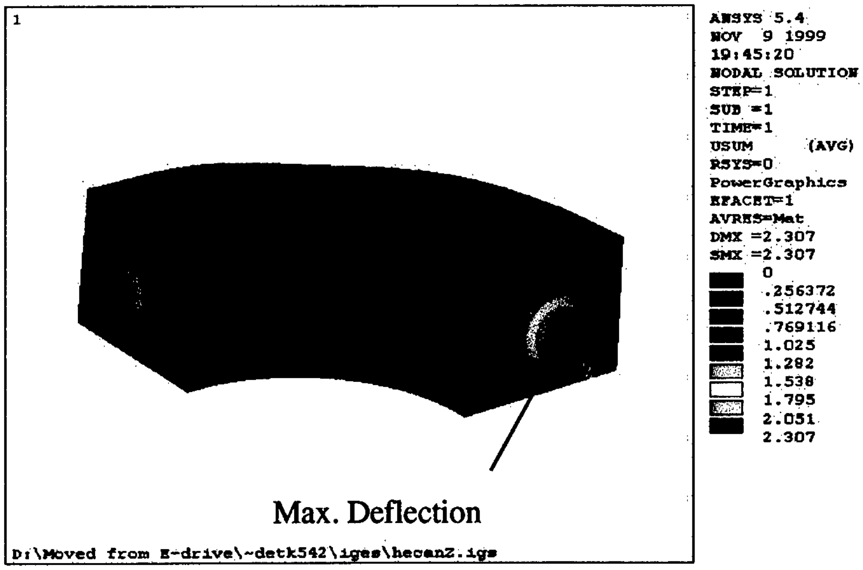
walls and provide an interface for attachment of access doors. Design iterations on the composite wall thickness and steel frame thickness were performed until acceptable positive margins were achieved in the composite wall and steel framing.

Figures 16 and 17 present representative displacement and stress results for the 3-D solid model of the HE can with a 0.25 inch wall thickness and a 0.25 inch steel frame thickness. For this model, the steel frame was located at the corners and along the top edge of the HE can. This case results in a maximum displacement greater than 2 inches and failure at the center of the side walls of the HE can, as indicated in Figure 16. In addition, the predicted maximum stress in the 0.25 inch thick steel frame exceeds the allowable ultimate strength for even a high strength steel such as 4340, as shown in Figure 17. It should be noted, however, that the predicted maximum displacements and stresses over most of the HE can area are below the allowable limits. This indicates that a non-uniform wall thickness, with thicker wall at the higher stress regions, could be used for the HE can to reduce weight. Since specific weight requirements were not established, a uniform wall thickness was established for the baseline design consistent with the conservative design approach.

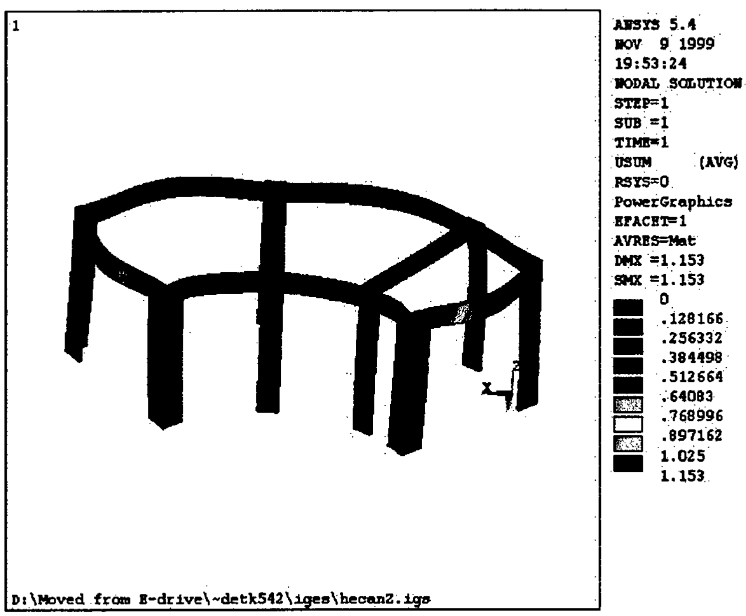
Based on the results for the 0.25 inch wall and frame model, the thickness of the composite wall was increased to 0.50 inches. This resulted in an 84% reduction in the predicted maximum displacement compared to the 0.25 inch wall. A high positive margin of safety of 0.96 was obtained for the maximum equivalent stress in the HE can side wall. The maximum displacement at this location was 0.38 inches. Increasing the composite wall thickness also reduced the maximum frame displacement by 75%. Except for small regions of locally high stress concentration, the predicted stresses in the steel frame for this case were lower than the allowable ultimate strength for 4340 steel (σ = 287 ksi). Except in the side wall region, the predicted maximum stresses were below the ultimate strength for carbon structural steel (e.g., ASTM A36, σ = 80 ksi). Figures 18 and 19 present the displacement and stress contours for the 0.5 inch composite wall with a 0.25 inch thick steel frame.

In an effort to reduce the weight of the steel frame, the thickness of the frame was reduced to 0.125 inches for the 0.50 inch thick composite wall model. Representative results for this case are presented in Figures 20 and 21. With the thinner steel frame, there is a 7% increase in stress and a 23% increase in displacement for the composite wall vs. the 0.25 inch thick frame. The maximum stresses in the steel frame were below the allowable strength for 4340 steel.

The 3-D solid model for the 0.50 inch thick composite wall with the 0.25 inch thick frame was further modified to include additional frame reinforcement at the top of the can to accommodate the lids and strengthen the frame in this region. Representative displacement and stress contours for this case are shown in Figure 22 and 23. For this case, high positive margins were obtained for the composite and steel frame. Based on these results, the 0.50 inch S2 glass/epoxy composite wall design with a 0.25 inch thick

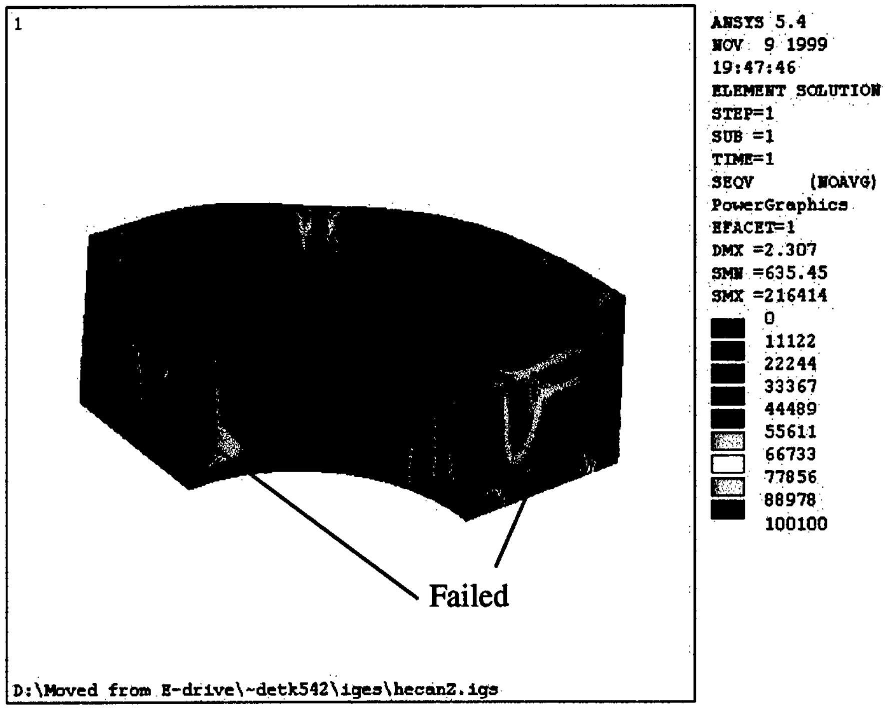


a.) Composite wall.

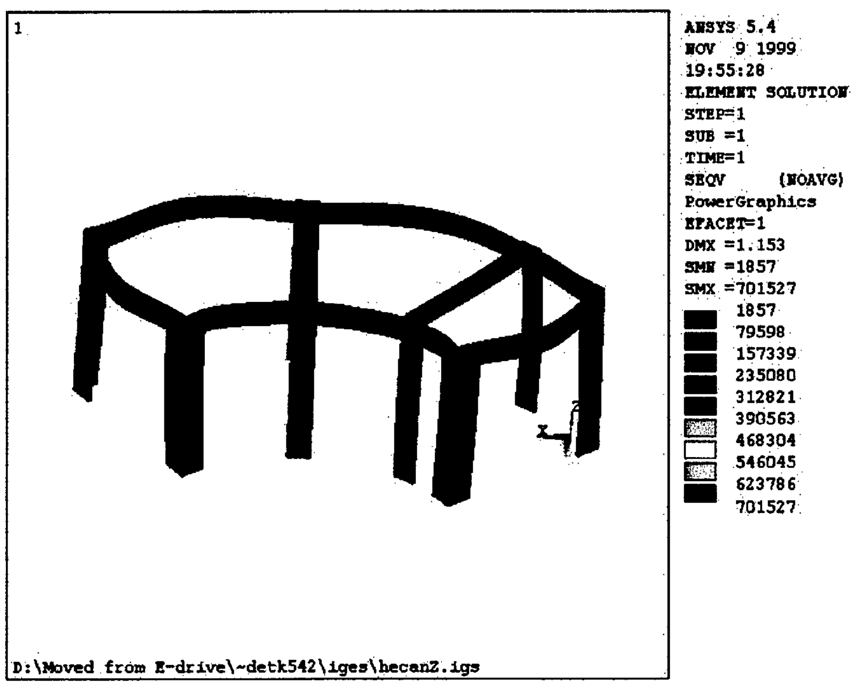


b.) Steel side frame.

Figure 16. Representative displacement results for the 3-D solid model of the HE can with a 0.25 inch wall thickness and a 0.25 inch thick steel side frame.

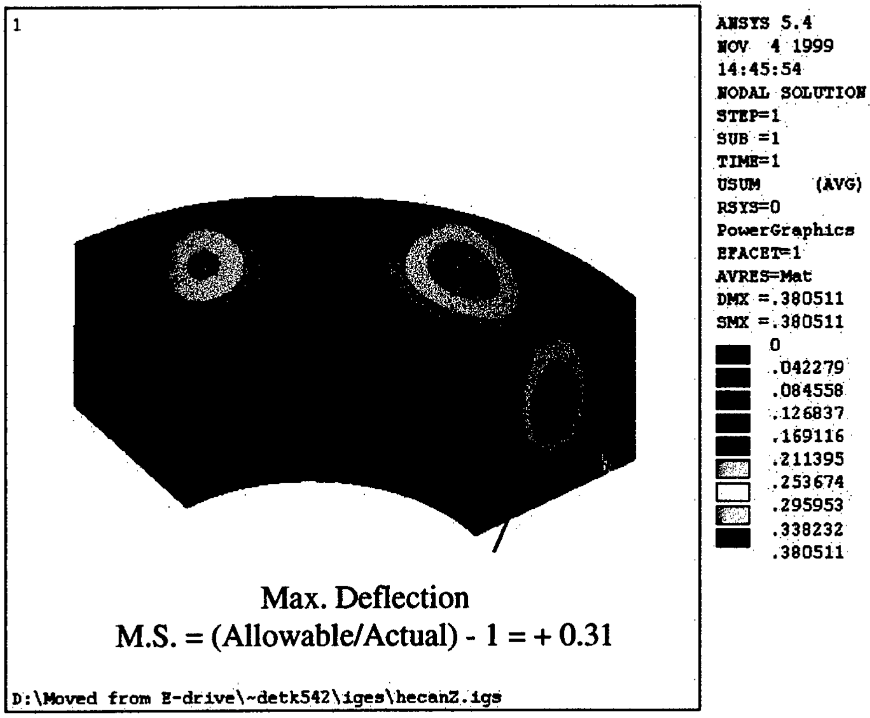


a.) Composite wall.

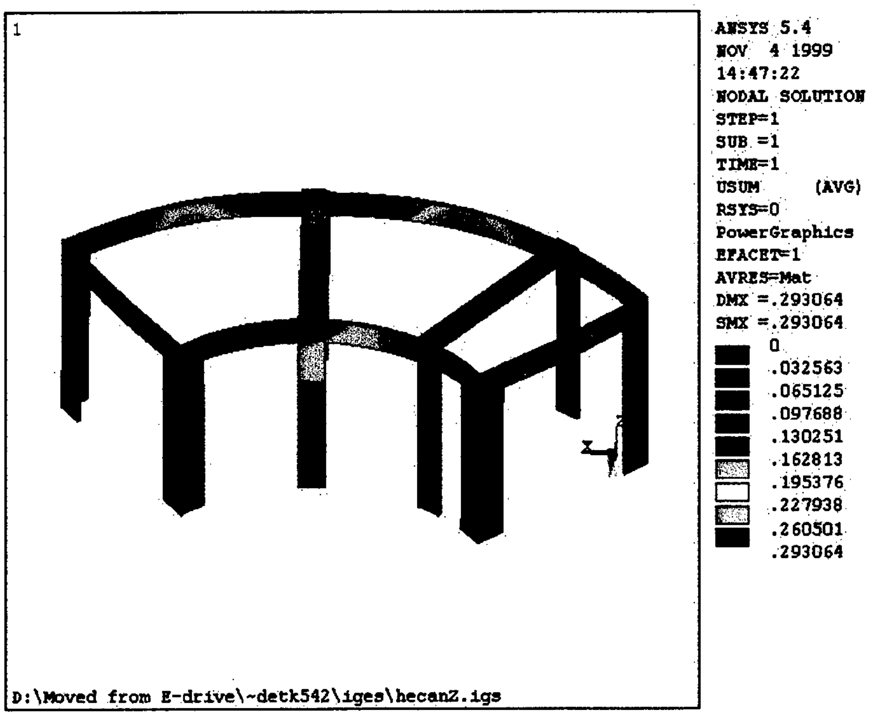


b.) Steel side frame.

Figure 17. Representative stress results for the 3-D solid model of the HE can with a 0.25 inch wall thickness and a 0.25 inch thick steel side frame.

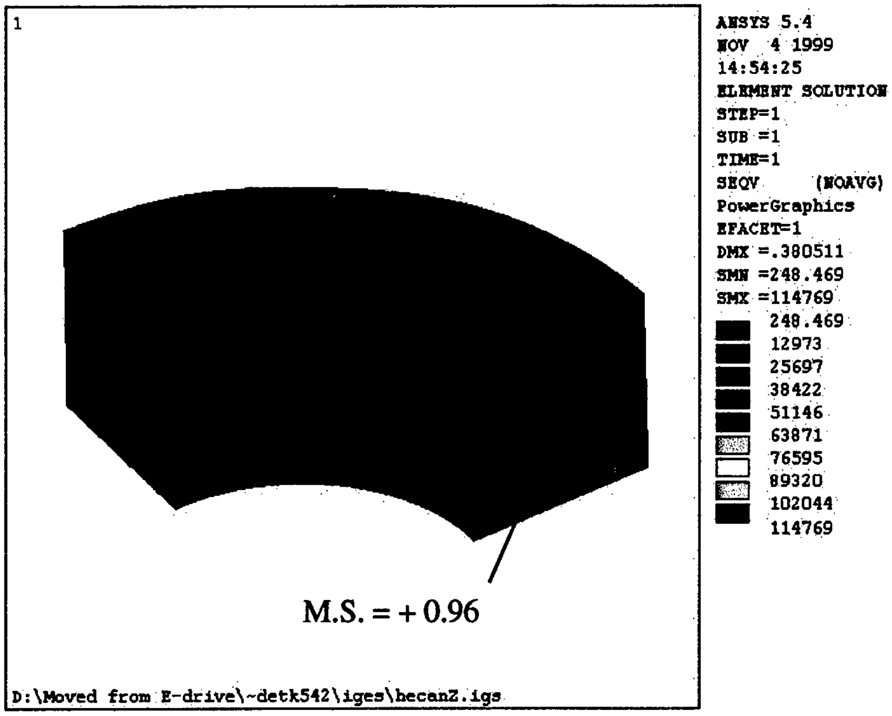


a.) Composite wall.

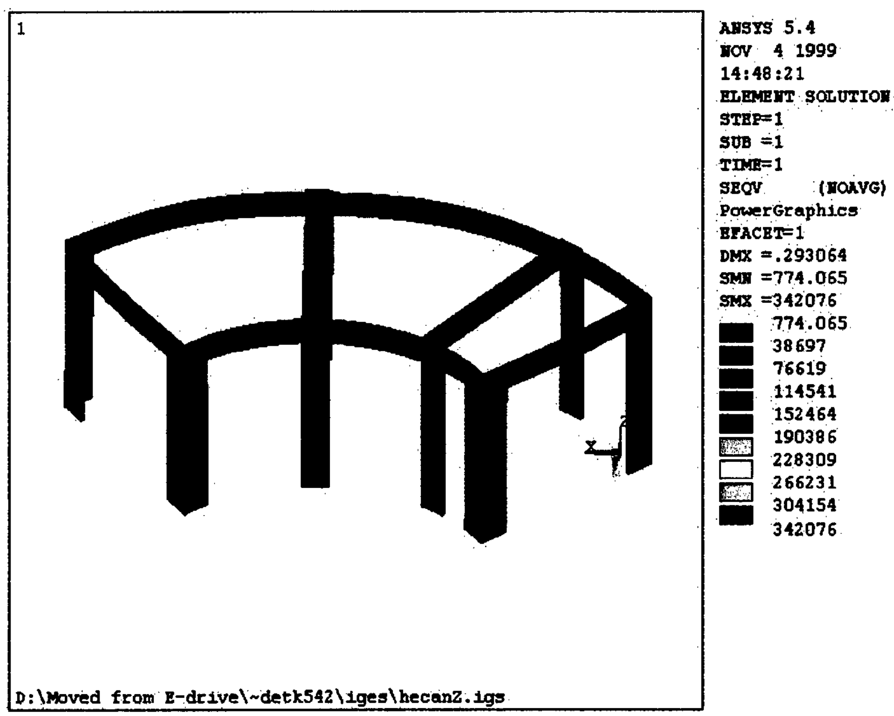


b.) Steel side frame.

Figure 18. Representative displacement results for the 3-D solid model of the HE can with a 0.50 inch wall thickness and a 0.25 inch thick steel side frame.

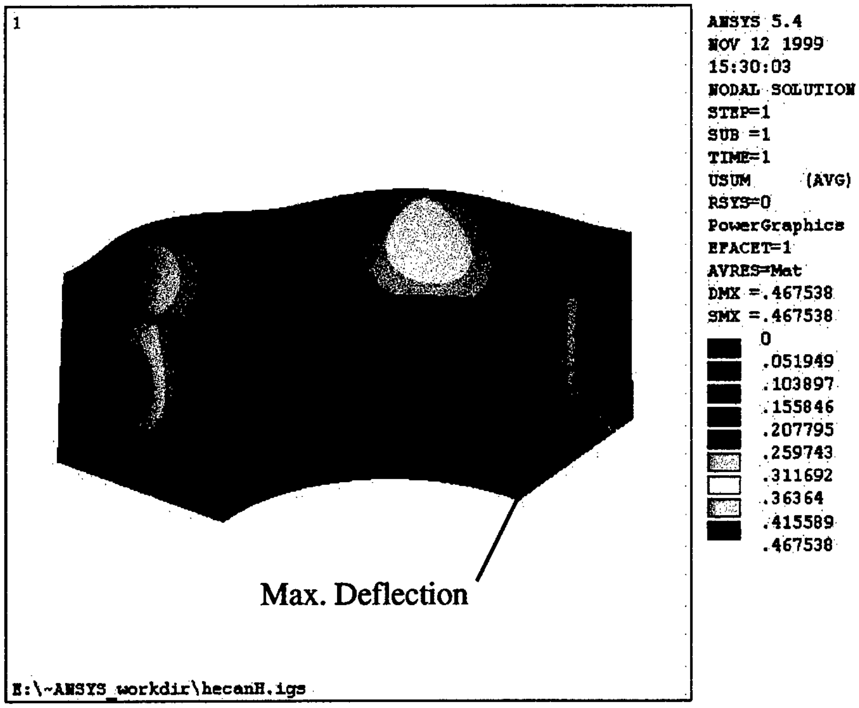


a.) Composite wall.

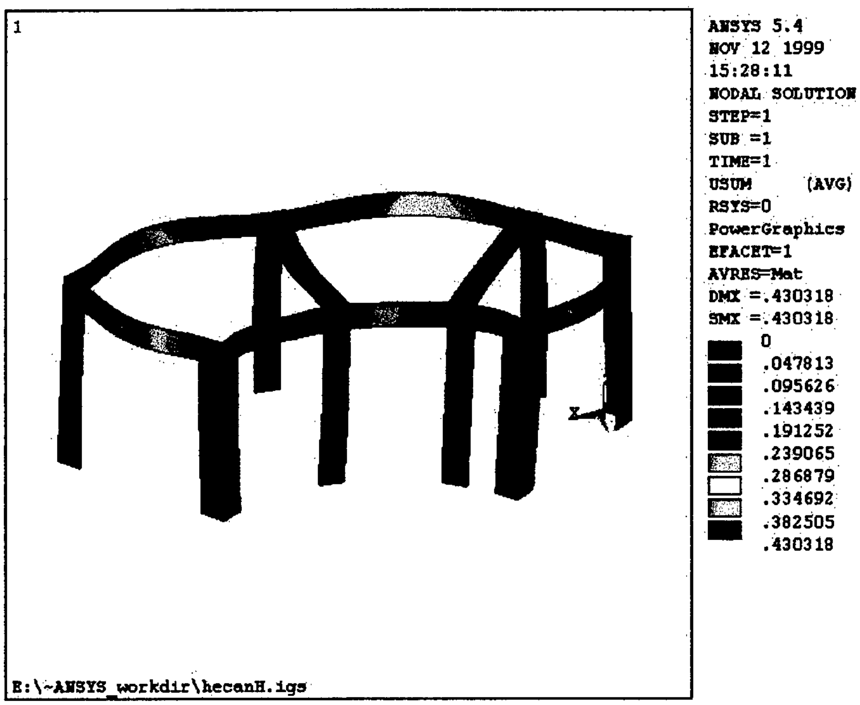


b.) Steel side frame.

Figure 19. Representative stress results for the 3-D solid model of the HE can with a 0.50 inch wall thickness and a 0.25 inch thick steel side frame.

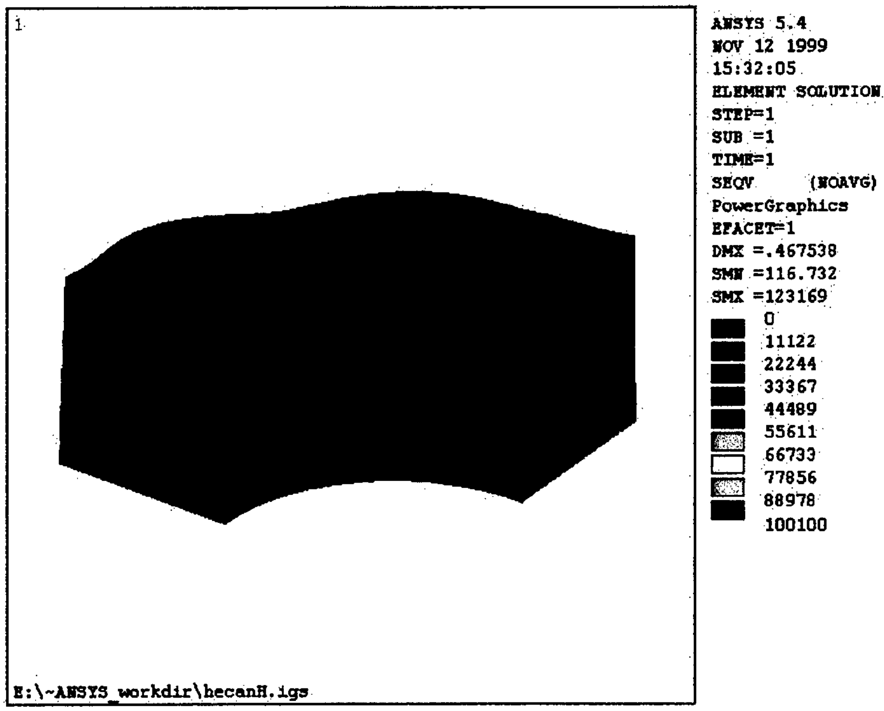


a.) Composite wall.

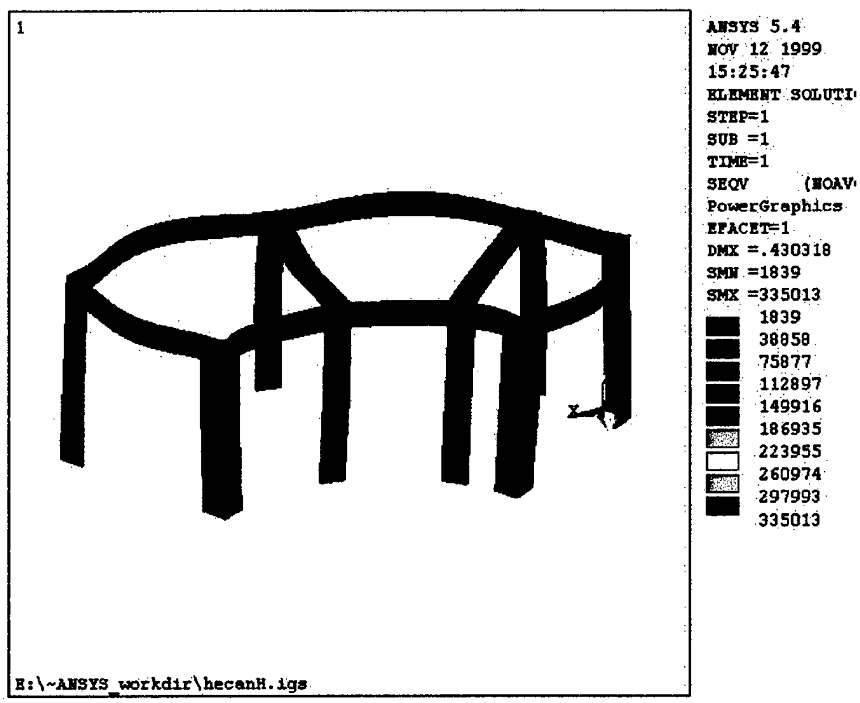


b.) Steel side frame.

Figure 20. Representative displacement results for the 3-D solid model of the HE can with a 0.50 inch wall thickness and a 0.125 inch thick steel side frame.

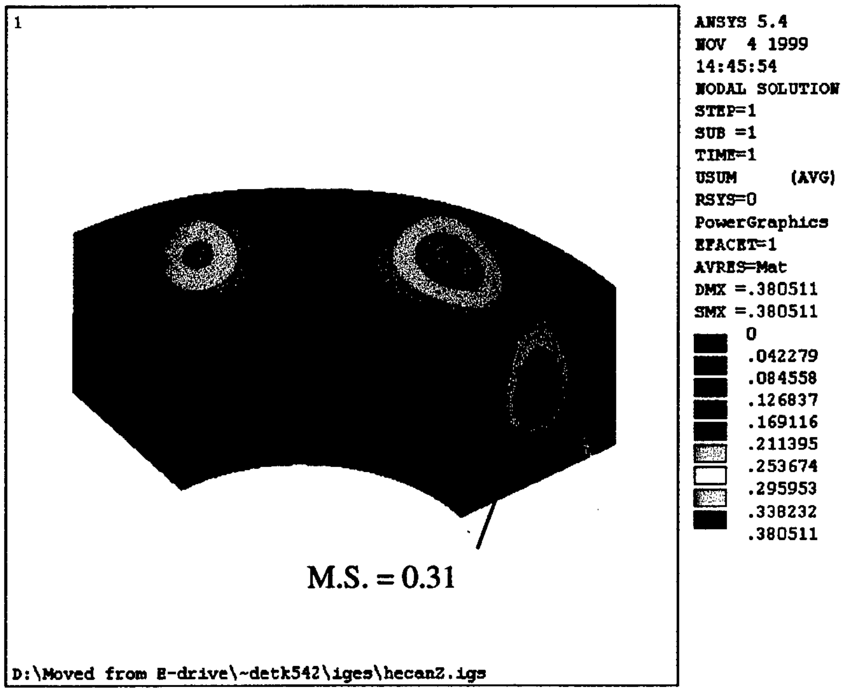


a.) Composite wall.

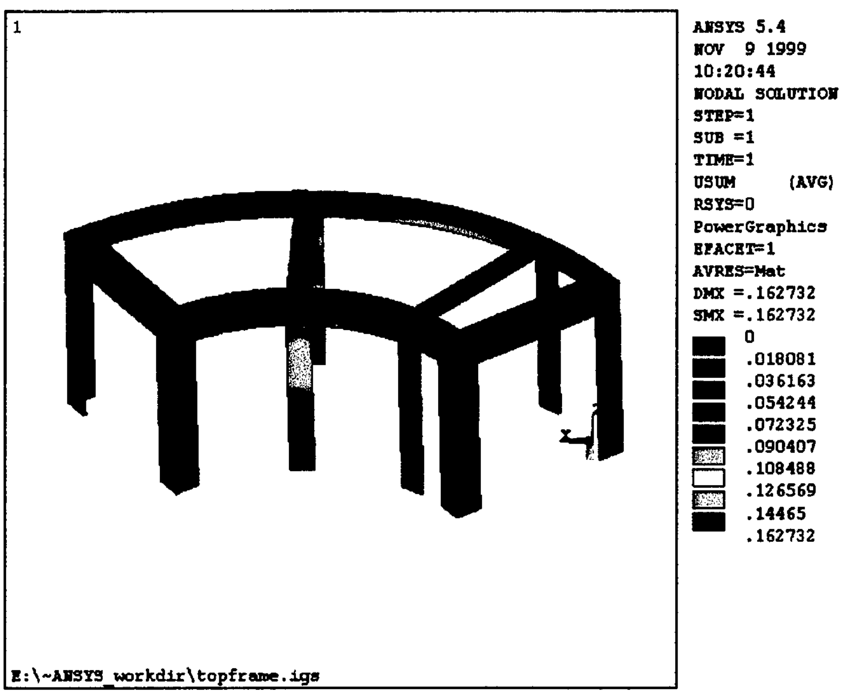


b.) Steel side frame.

Figure 21. Representative stress results for the 3-D solid model of the HE can with a 0.50 inch wall thickness and a 0.125 inch thick steel side frame.

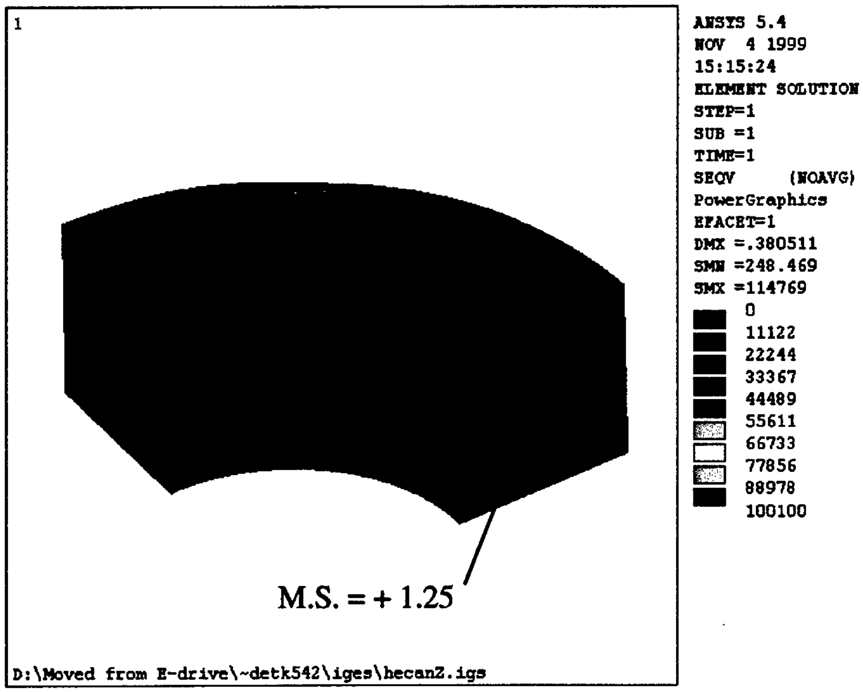


a.) Composite wall.

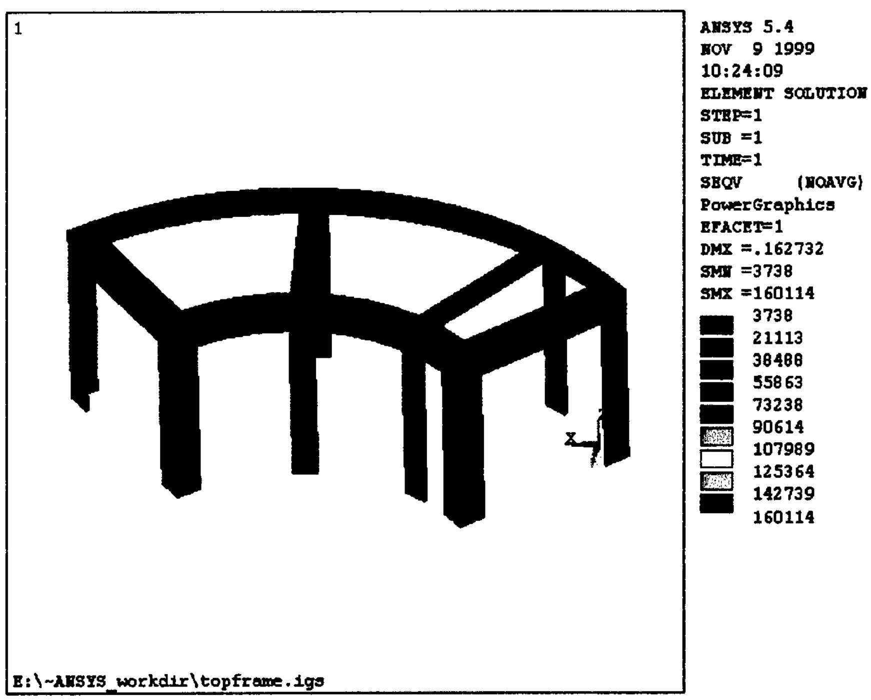


b.) Steel full frame.

Figure 22. Representative displacement results for the 3-D solid model of the HE can with a 0.50 inch wall thickness and a 0.25 inch thick steel full frame.



a.) Composite wall.



b.) Steel full frame.

Figure 23. Representative stress results for the 3-D solid model of the HE can with a 0.50 inch wall thickness and a 0.25 inch thick steel full frame.

full steel frame was selected for the prototype design. As previously discussed, the design of the HE can assumes a uniform wall thickness in accordance with the conservative design approach. Once specific weight constraints are established, it is envisioned that significant weight reductions could be achieved by using a non-uniform wall thickness design in which the front and back walls are thinner (e.g., 0.25 inches) than the side walls.

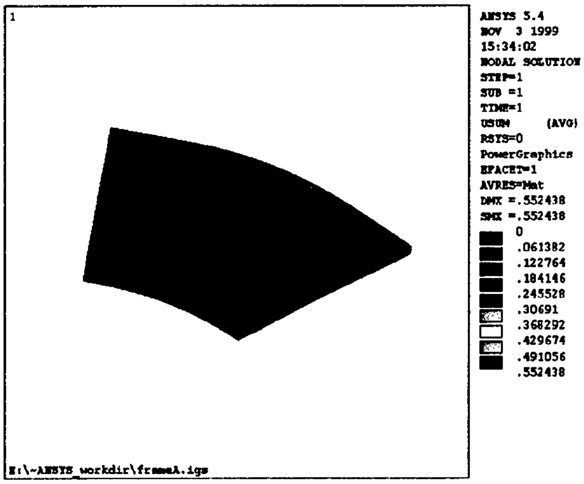
Finite element analyses of the HE container lid was also performed using ANSYS to evaluate maximum displacements and stresses. Two lid configurations were analyzed: (1) a 0.50 inch glass/epoxy wall with a 0.25 inch frame around the edges, and (2) a 0.50 inch glass/epoxy wall with 0.25 inch thick frame around the edges and across the center. Figures 24 and 25 present the representative stress contours for these two cases, respectively. The predicted maximum displacement for the first case was 0.55 inches at the center of the lid. Reinforcing the composite pressure wall using a steel plate across the lid, as shown in Figure 25, reduced the maximum displacement to 0.176 inches and produced high positive margins in the composite wall.

Based on the results of the FEA, the 0.50 inch glass/epoxy wall with the 0.25 inch full steel frame was selected for the HE ready container and lid prototype design. Table 6 summarizes the results of the 3-D finite element analysis for the HE ready container and lid. As shown in the Table, the maximum displacement of the HE ready container for the 0.50 inch wall with a 0.25 inch full steel frame reinforcement is 0.380 inches. The maximum equivalent composite stress is 44.5 ksi. The maximum equivalent stress in the steel frame for this configuration is 73.2 ksi. The maximum displacement predicted for a 0.50 inch thick composite lid with additional steel plate reinforcement across the center is 0.176 inches. The maximum composite stress in the lid for this case is 43.3 ksi.

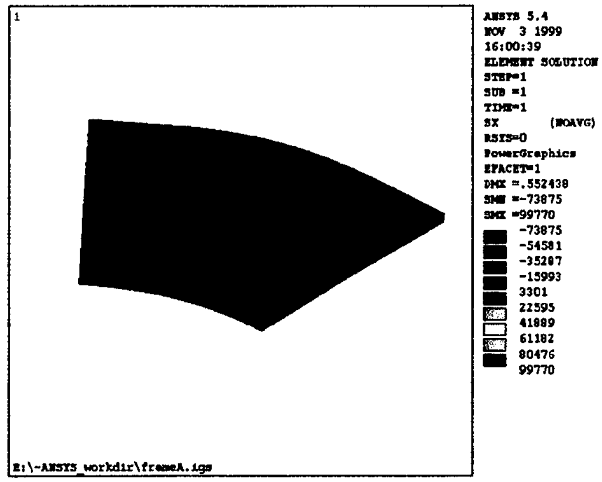
As previously discussed, the FEA of the HE ready container design indicates that the weight of the recommended prototype design could be significantly reduced by using a non-uniform wall thickness design. The Phase I program schedule and funding did not allow for evaluation of an optimized HE ready container design. However, it is recommended that an optimized pressure wall design be evaluated at the onset of a follow-on Phase II development and demonstration program. Analyses of a lighter weight design should also consider reducing the thickness of the steel reinforcement in certain areas, based on the Phase I analysis results.

VIII. Solid Model of Ammunition Container System

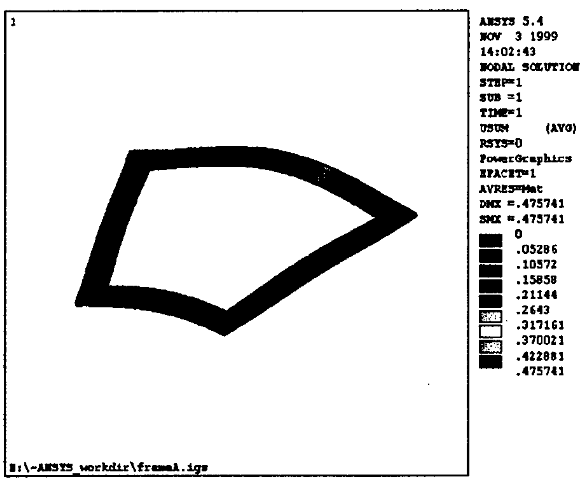
In conjunction with the FEA, solid models of the ammunition containment assembly were generated using Mechanical Desktop® for model development and design presentation purposes. The solid models were also used to define approximate geometries and to identify potential interferences with existing AAAV components (e.g., turret integration assembly, gun feed, etc.) The solid models were primarily generated from hard copy drawings of the existing AAAV ammunition container, feed system and



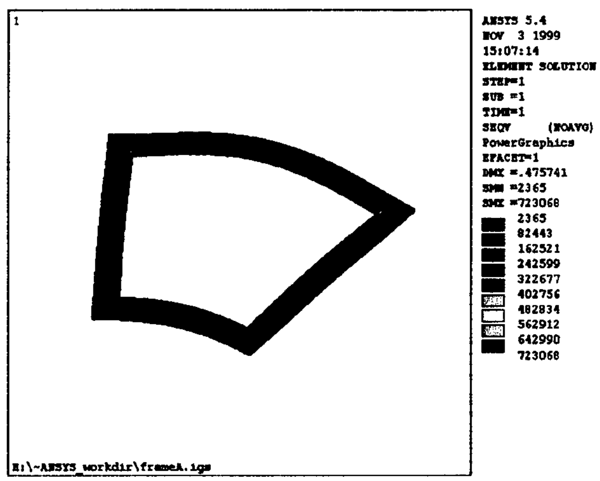
a.) Composite wall displacement.



b.) Composite wall stress.

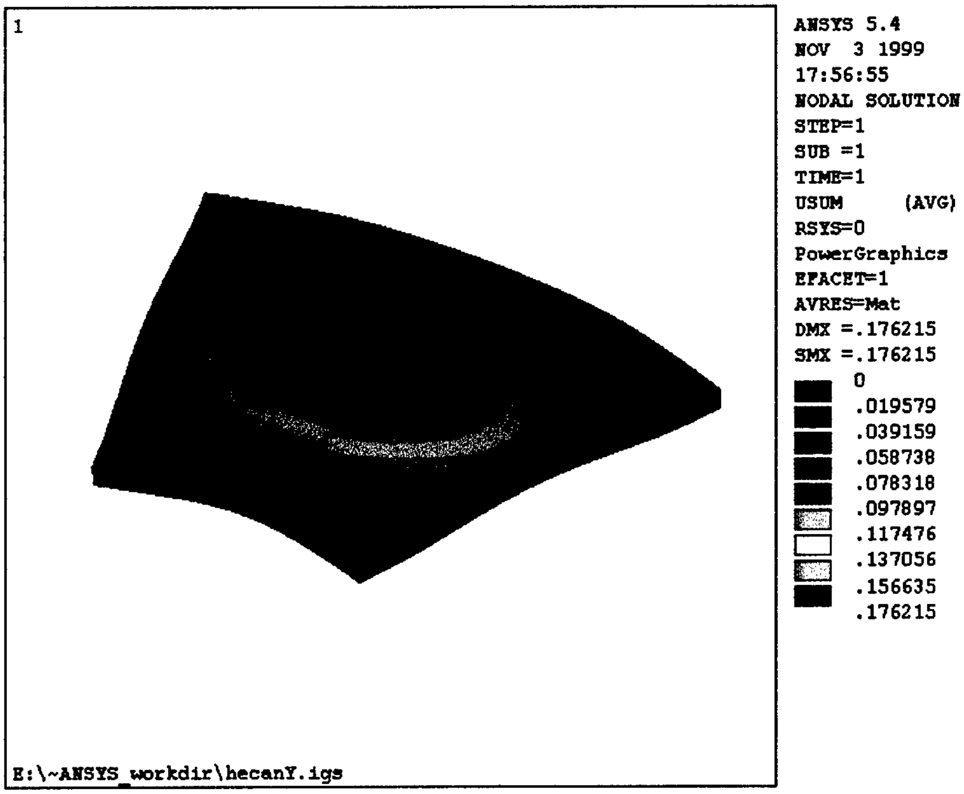


c.) Steel comer frame displacement.

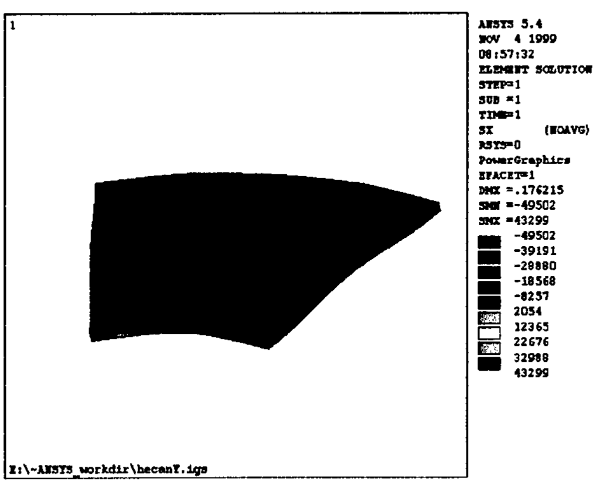


d.) Steel corner frame stress.

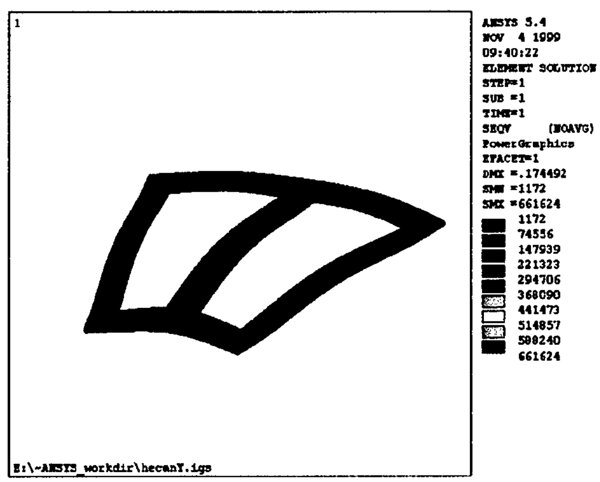
Figure 24. Representative displacement and stress results for the 3-D solid model of the HE lid with a 0.50 inch wall thickness and a 0.25 inch thick steel corner frame.



a.) Displacement.



b.) Composite stress.



d.) Steel corner/mid frame stress.

Figure 25. Representative displacement and stress results for the 3-D solid model of the HE lid with a 0.50 inch wall thickness and a 0.25 inch thick steel corner and center frame.

Table 6. Pressure containment wall design summary.

Component	Design Configuration	Material Layer	Max. Displacement (in.)	Max. Stress (ksi)
HE Ready Container	1/4" S2 Glass/Epoxy Wall with 1/4" Side Frame	S2 Glass/Epoxy	2.307	144.5
		Steel Frame	1.153	390.6
	1/2" S2 Glass/Epoxy Wall with 1/4" Side Frame	S2 Glass/Epoxy	0.380	51.1
		Steel Frame	0.293	152.5
	1/2" S2 Glass/Epoxy Wall with 1/8" Side Frame	S2 Glass/Epoxy	0.468	54.8
		Steel Frame	0.430	186.9
	1/2" S2 Glass/Epoxy Wall with 1/4" Full Frame	S2 Glass/Epoxy	0.380	44.5
		Steel Frame	0.163	73.2
HE Ready Container Lid	1/2" S2 Glass/Epoxy Wall with 1/4" Frame, Clamped at corners of frame with 1/2" composite wall	S2 Glass/Epoxy	0.552	99.8
		Steel Frame	0.476	242.6
	1/2" S2 Glass/Epoxy Wall with 1/4" Frame, Clamped at corners and in center of frame with 1/2" composite wall	S2 Glass/Epoxy	0.176	43.3
		Steel Frame	0.176	147.9
Allowable		S2 Glass/Epoxy	0.5	100.1
		Low Carbon Steel, ASTM A36	0.5	80
		High Strength Steel, 4340	0.5	287

turret ring design, as provided by General Dynamics. Solid model files of the turret shelf and outer walls were not provided until near the end of the Phase I program period of performance. It is recommended that the solid model of the final recommended ammunition containment system assembly be integrated into the most current AAAV solid model files to check for possible interference and confirm estimated volumes and vent area locations.

VIII.a Sub-Assemblies

The solid model of the ammunition containment system, illustrated in Figure 26, consists of four main sub-assemblies: (1) the ready container, (2) the feed tower, (3) the turret enclosure and (4) the gun feed. The configuration shown was designed to be compatible with the provided AAAV container and feed system design geometry, allowing no changes to the feed system design. This is significant in that the current feed system geometry does not lend itself to containment using a simpler, potentially more efficient pressure vessel geometry (i.e., cylinder). As a result, more composite material reinforcement is required for the side walls and corners. In addition, the requirement for access to ammunition in the feed system further complicates the geometry and structural reinforcement. In order to enclose the entire feed system, a larger (and, consequently, heavier) structure is required. It is strongly recommended that a follow-on Phase II development program involve concurrent engineering of the ammunition feed system and containment system to arrive at the most efficient design.

As illustrated in the solid model shown in Figure 26, access doors are provided on the ready container and feed system to provide access to the stored ammunition and still maintain pressure retention and sealing capability when closed. Handles and latches are provided for simple removal of the doors. The prototype design includes two doors at the top of the HE ready container and three doors on the crew compartment wall of the feed tower. The lower feed tower door provides access to the AP ammunition container. The containment system would extend to the inner wall of the turret, as shown, to completely contain the gases and allow venting operation. The design of the gun feed system containment includes outer containment walls with an opening to allow extension of the upper gun feed system throughout the range of motion of the gun. Although design details were not finalized in Phase I, the concept shown involves a movable tube-in-tube enclosure with a flexible composite connection to the gun.

VIII.a.1 HE/AP Ready Container

The solid model representation of the HE and AP ammunition containment assembly underwent continued refinement and enhancement in conjunction with the design and analysis effort in Phase I. Upgrades were made to the initial HE can solid model to incorporate increased composite layer and steel frame thicknesses as determined from the ANSYS finite element analyses. Specific design features such as the lids,

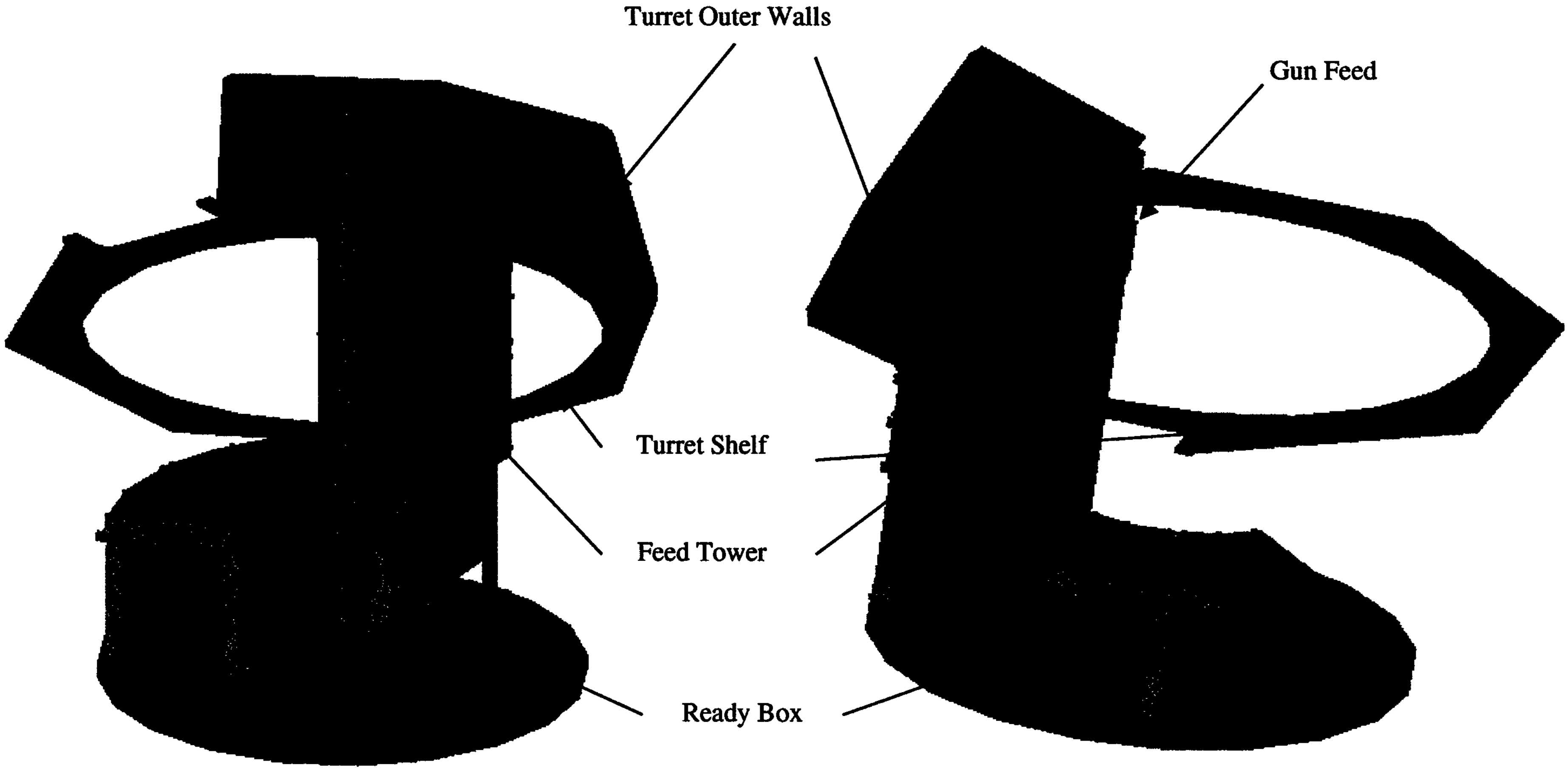


Figure 26. Solid model of ammunition containment system.

frame, attachments, and access doors were incorporated into the solid model as the design development progressed.

As shown in Figure 27, the integral HE/AP ammunition ready container was divided into three basic elements for our design effort. The three elements are the tub, frame, and lids, as shown. The tub is the bottom and side walls of the ammunition ready container. The tub is constructed of the armored pressure vessel wall lay-up previously described. The frame is a structural member which is used to provide reinforcement of the HE/AP ready container and to attach the tub to the lids. The lids are constructed of the armored pressure vessel wall lay-up within a frame surround. The lids provide direct access to the ammunition ready container. Gaskets are located between the frame and HE/AP container and between the lids and the frame to seal the internal gases.

Means of attaching the elements to each other and securing the container to the turret floor were investigated. The required attachment points are: container to floor, frame to tub, and lid to frame. Two concepts were considered for use as attachment methods. The first method would have separate feet and frame assemblies which would be bolted to the tub. The second method would use a support strut to attach the frame to the feet.

The bolted concept was not selected for further investigation for two reasons. The through holes in the tub will weaken the composite wall structure requiring the addition of inserts to maintain strength. In addition, there is a possibility of shearing the bolt and projecting it into the crew compartment if an HE round were to detonate in close proximity of the bolt.

The strut concept was adopted for future development. In this concept there are no intrusions into the tub area maintaining the integrity of the composite system. The struts add support to the tub side walls and stiffen the total structure, thus reducing the outer composite wall thickness. The strut would be welded to the frame and bolted to the floor. A gasket will be used around the top of the tub and a compressive load will be maintained between the tub and frame when the frame is attached to the turret floor. A shelf is welded to the frame assembly for attachment the AP ammunition ready container.

Trade studies were performed to determine the size, number, and shape of the struts. The frame and support structure was also analyzed. Angles are used on the four corners of the assembly and C-channels are used on the intermediate support struts and at the tower joint area. The angles and channels are all 0.25 inches in thickness. The angle dimensions are 2" x 2" and the C-channel dimensions are 2" x 0.5".

VIII.a.2 Feed Tower

The solid model of the feed tower concept is shown in Figure 28. The model includes the multi-layer composite containment wall, steel framing, access doors and attachments. The geometry of the tower was designed to fit around the existing feed rail

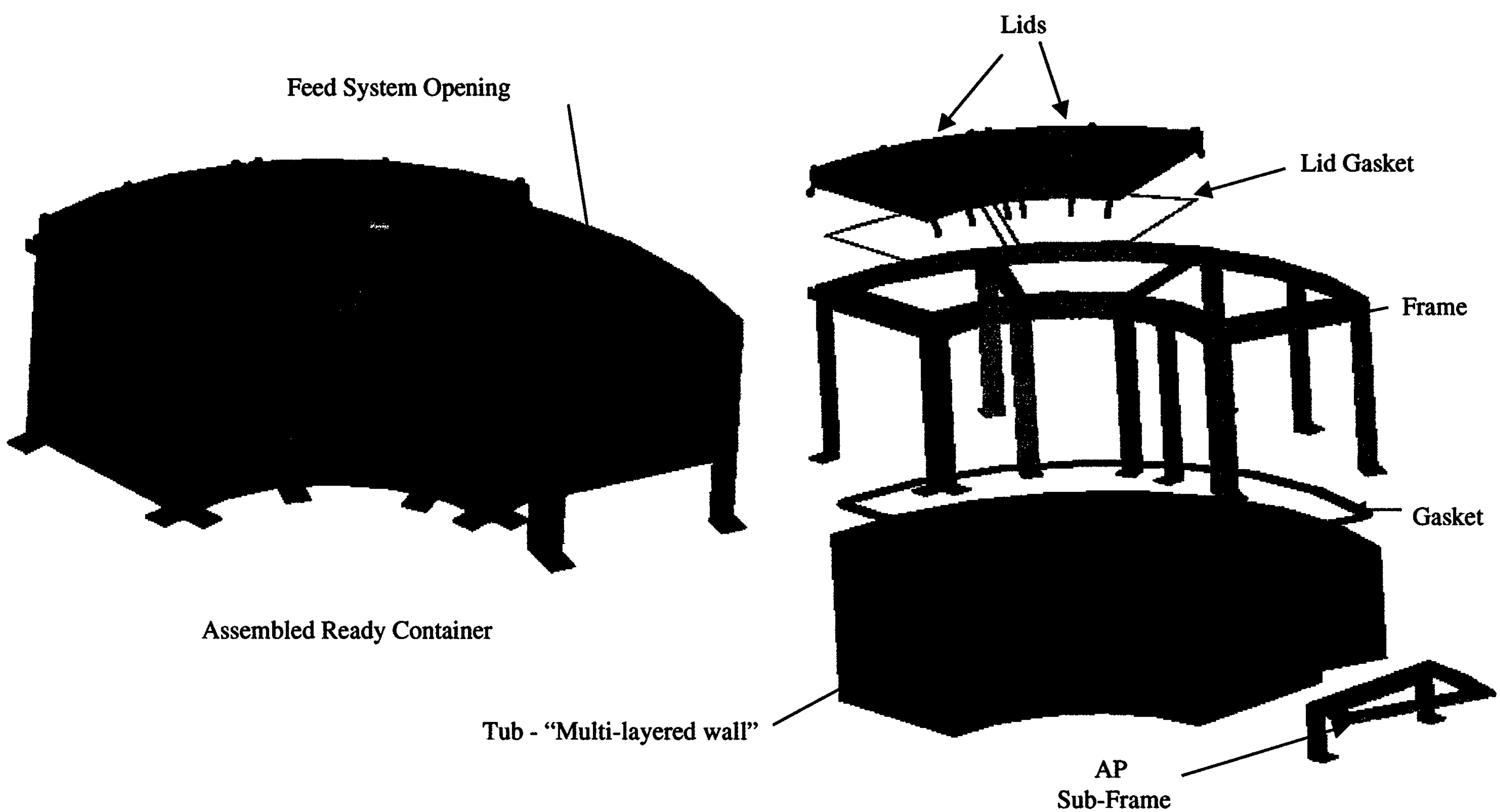


Figure 27. Solid model of integral HE/AP ammunition ready container.

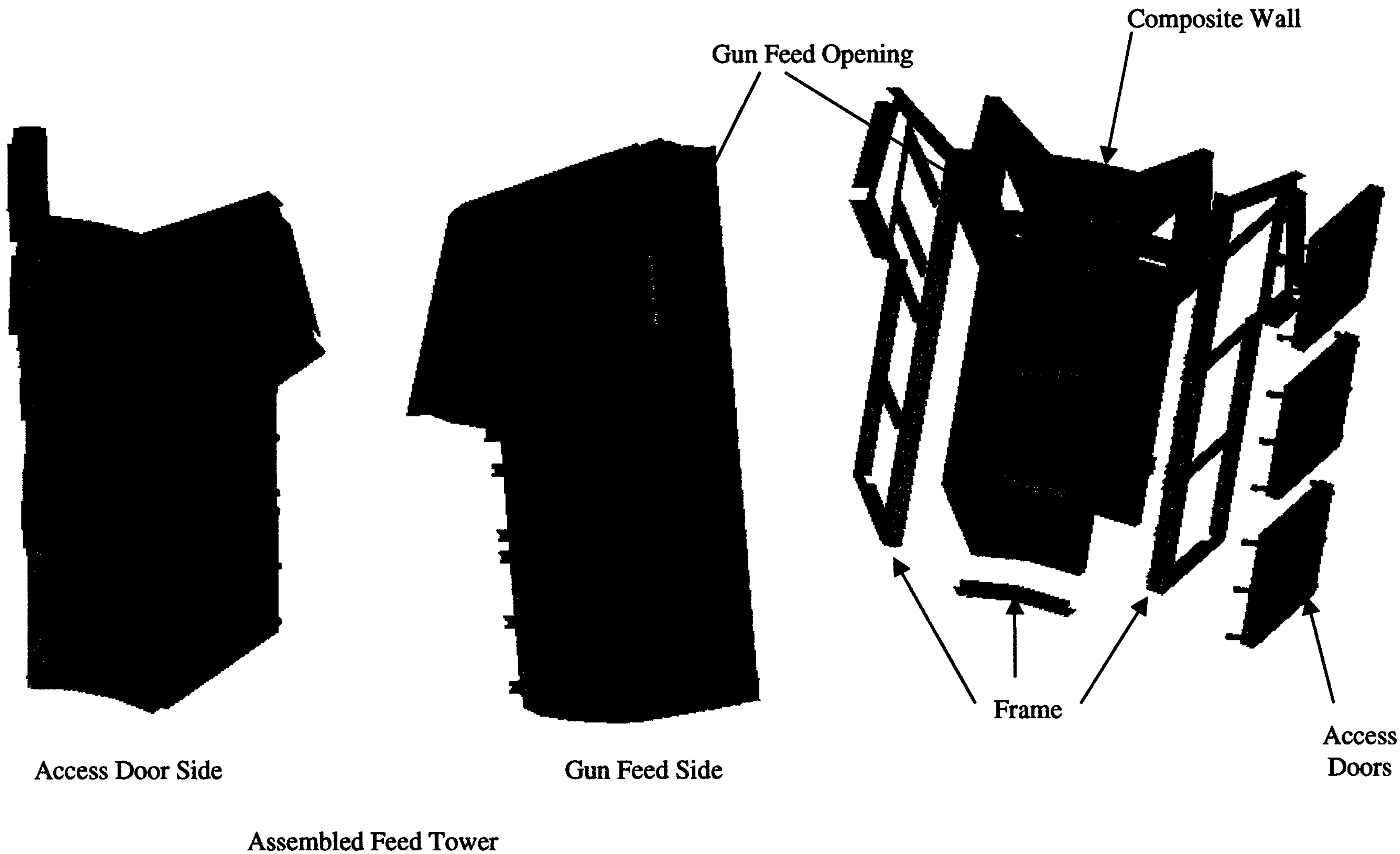


Figure 28. Solid model of the feed tower concept .

system with minimal clearance. Since only the 2-D drawings were provided at the onset of the Phase I program, the development of the solid model of the feed tower is considered to be a "representation" of the design concept. Integration with the 3-D solid model of the feed rail system is required to develop the final design details.

For the feed tower, three access doors are located on the crew compartment wall, as shown. The lower door provides access to the AP ammunition container. Attachment and sealing of the access doors is identical to that for the HE ready container, with handles attached to the lid frame and latches attached to the side wall frame. In this design configuration, the steel framing would have to be welded in place around the molded composite wall, with thermal insulation material placed in between. The solid model shown in Figure 28 also shows the opening for the gun feed which allows for the full range of gun motion.

VIII.a.3 Turret Enclosure

Integration of the feed tower and upper gun feed section with the turret walls and turret shelf is shown in an exploded view in Figure 29. The location of the vent holes in the turret shelf is also shown. The framing at the upper section of the feed tower provides an attachment interface to the armored turret wall panels.

VIII.a.4 Gun Feed

The design of the gun feed containment system presents a significant challenge in that containment must encompass the full range of gun motion, as represented by the minimum and maximum elevations shown in Figure 30. Also, the areas of the gun breach which must be enclosed also need to be defined. In order to accommodate gun motion, the gun feed containment must include a movable, flexible composite structure.

Design options identified for the gun feed system include: (1) a sliding, hinged tube-in-tube concept; (2) a movable wall panel with a flexible composite connection to the gun; and (3) a large containment wall enclosure. The large containment "wall" is considered to be the lowest risk approach, but may exceed available space/volume constraints. In order to finalize the containment system design, specific constraints must be defined in coordination with the USMC and General Dynamics. These constraints include the gun motion, breach attachment points and breach area to be enclosed.

VIII.b Wall Configuration Areal Densities and Weights

The solid model of the ammunition containment system was used to estimate weights for the multi-layer composite wall and framing for the HE/AP ready container, feed tower and lids. Table 7 summarizes the areal densities for the individual layers of the multi-layer containment design. The total wall areal density is 18 lb/ft^2.

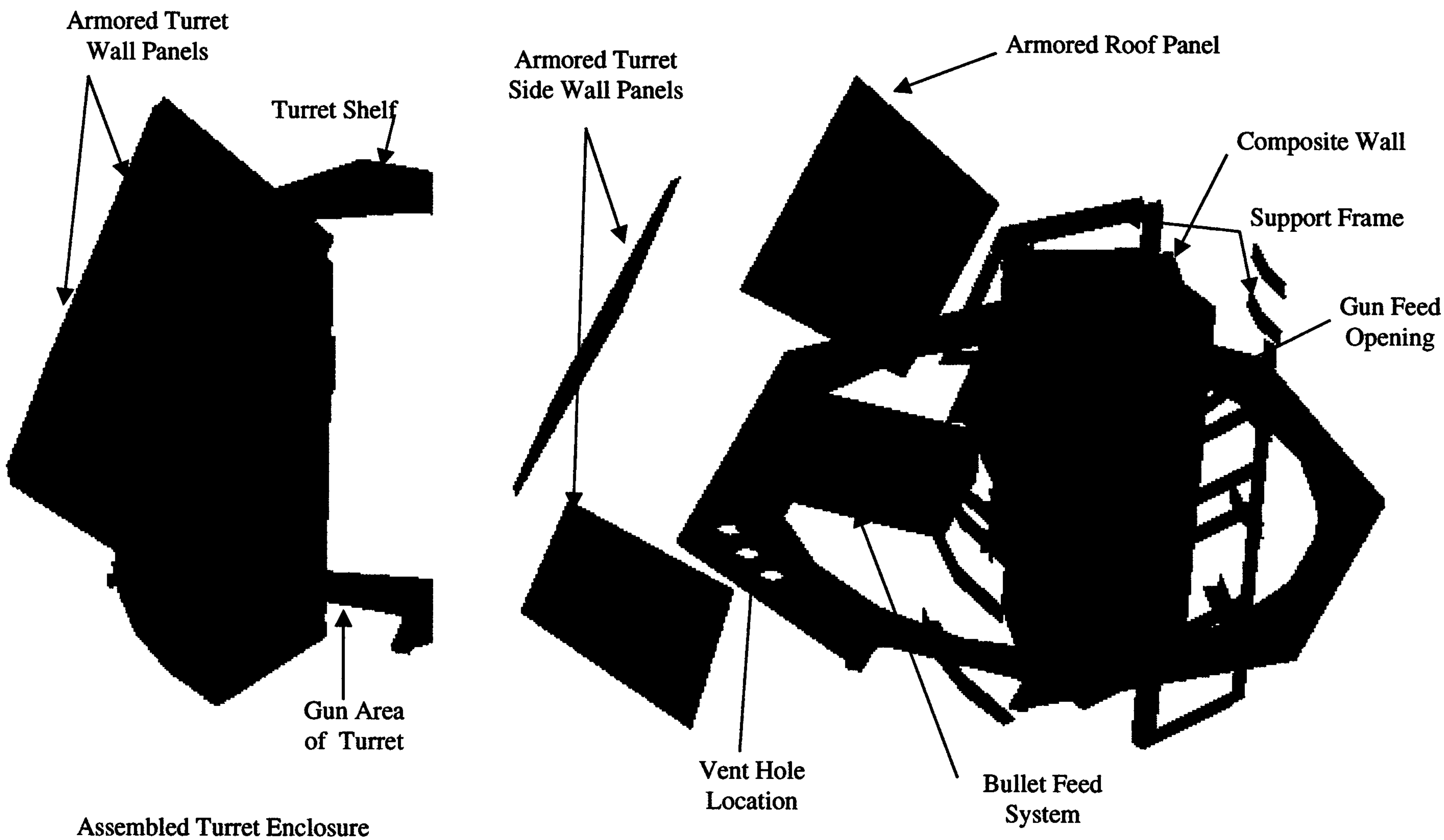


Figure 29. Solid model of the turret enclosure.

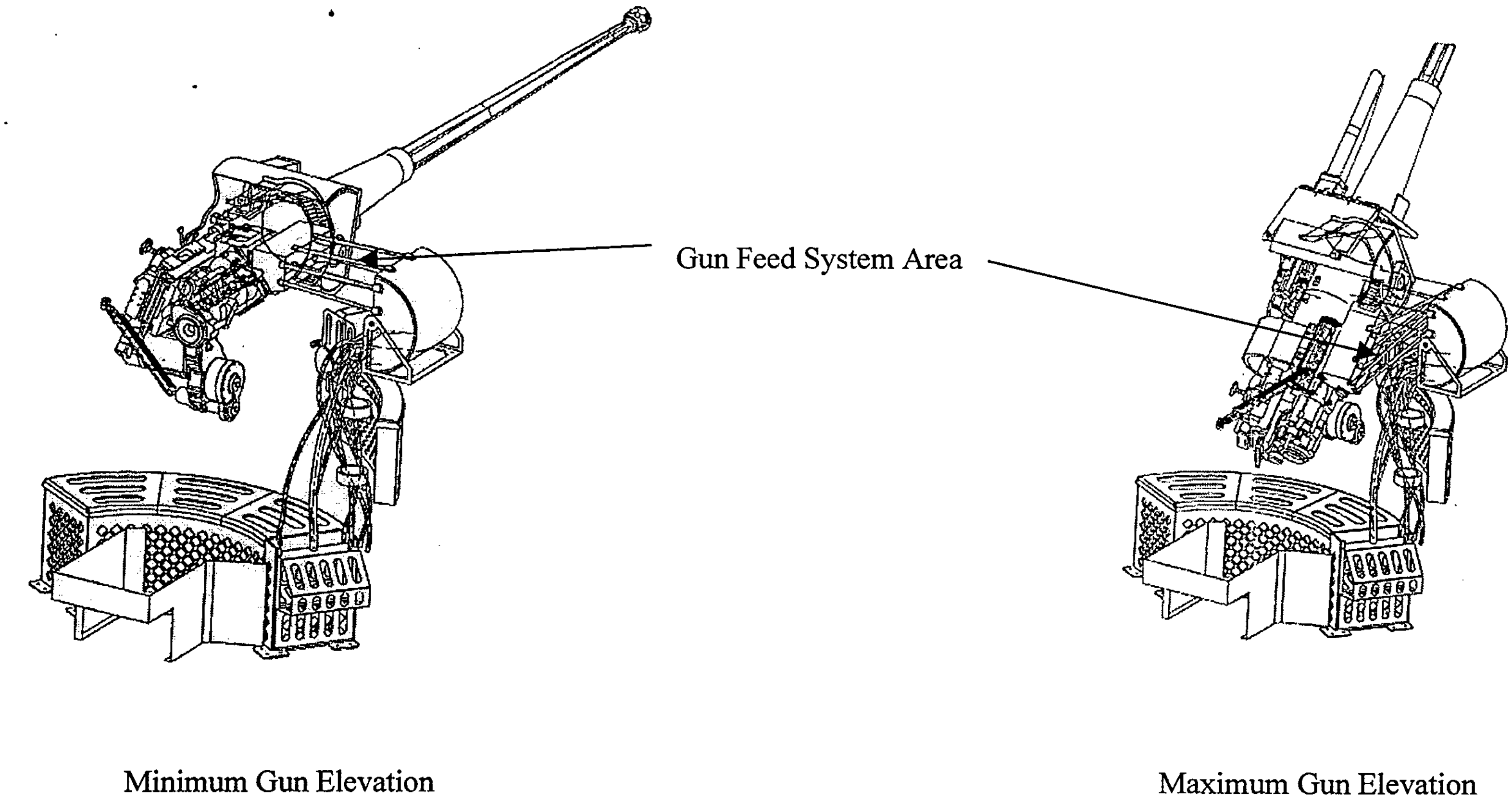


Figure 30. Gun range of motion.

Table 7. Areal Densities for Final Wall Configuration

Layer	Thickness(in.)	Material	Areal Density (lb/ft^2)
1 (Exterior)	0.50	S-2 Glass/Epoxy	5.04
2	0.50	Foam (20 pcf)	0.83
3	0.125	S-2 Glass/Epoxy	1.26
4	0.125	EPDM Rubber	0.79
5 (Interior)	0.250	Armor Steel	10.17
		TOTAL	18.09

The estimated weights for the ready container and feed tower walls, frames and lids are summarized in Table 8. Assuming uniform wall thicknesses for the composite walls and frames, the estimated weights for the ready container and feed tower are 461 lb and 963 lb, including walls, frames and lids. The heaviest components are the walls of the ready can and feed tower and the frame for the feed tower. Although no specific weight constraints were provided for the ammunition containment system, the total estimated weight of 1424 lbs is considered to be too high for practical implementation. Significant weight reduction could be achieved by reducing the wall thickness of the armor steel (by as much as half) in areas which do not protect the fragments generated by the HE rounds. This would result in approximately 5 lb/ft^2 weight savings. Also, as previously discussed, a non-uniform composite wall thickness could be used for pressure containment, reducing the thickness in the pressure wall over to 0.25 inches over most of the area.

IX. Manufacturing Approach

The recommended manufacturing approach for the composite ammunition containment system would involve a relatively low cost resin transfer molding (RTM) or vacuum assisted resin transfer molding (VARTM) process. Since the geometry includes curved and flat surfaces, corners, and locally reinforced areas, this process is considered to be more appropriate than filament winding or tape placement, for example. Furthermore, low cost tooling could be used to manufacture the individual components of the containment assembly. A more cost-effective approach is to use the inner steel armor and foam core as the tooling for application of the inner and outer fiberglass/epoxy composite layers, respectively.

The proposed manufacturing process is illustrated for the integral HE/AP ready ammunition container in Figure 31. The welded steel inner armor tub is first fabricated and the elastomeric seal layer is then bonded to the exterior of the steel tub. The inner S-2 glass fabric layers would then be applied over the rubber layer and subjected to an RTM process. Similarly, the foam core layer could also serve as the tooling for the outer composite layer, as shown. The foam "tub" could be fabricated by either bonding

Table 8. Pressure containment wall design summary.

	Mass (lb)		
Component	Wall	Frame	Total
Ready Can	347	42	389
Ready Can Lid 1	28	8	36
Ready Can Lid 1	28	8	36
Sub Total	403	58	461
Tower Can	690	141	831
Tower Lid 1	28	16	44
Tower Lid 2	28	16	44
Tower Lid 3	28	16	44
Sub Total	774	189	963
Total	1177	247	1424

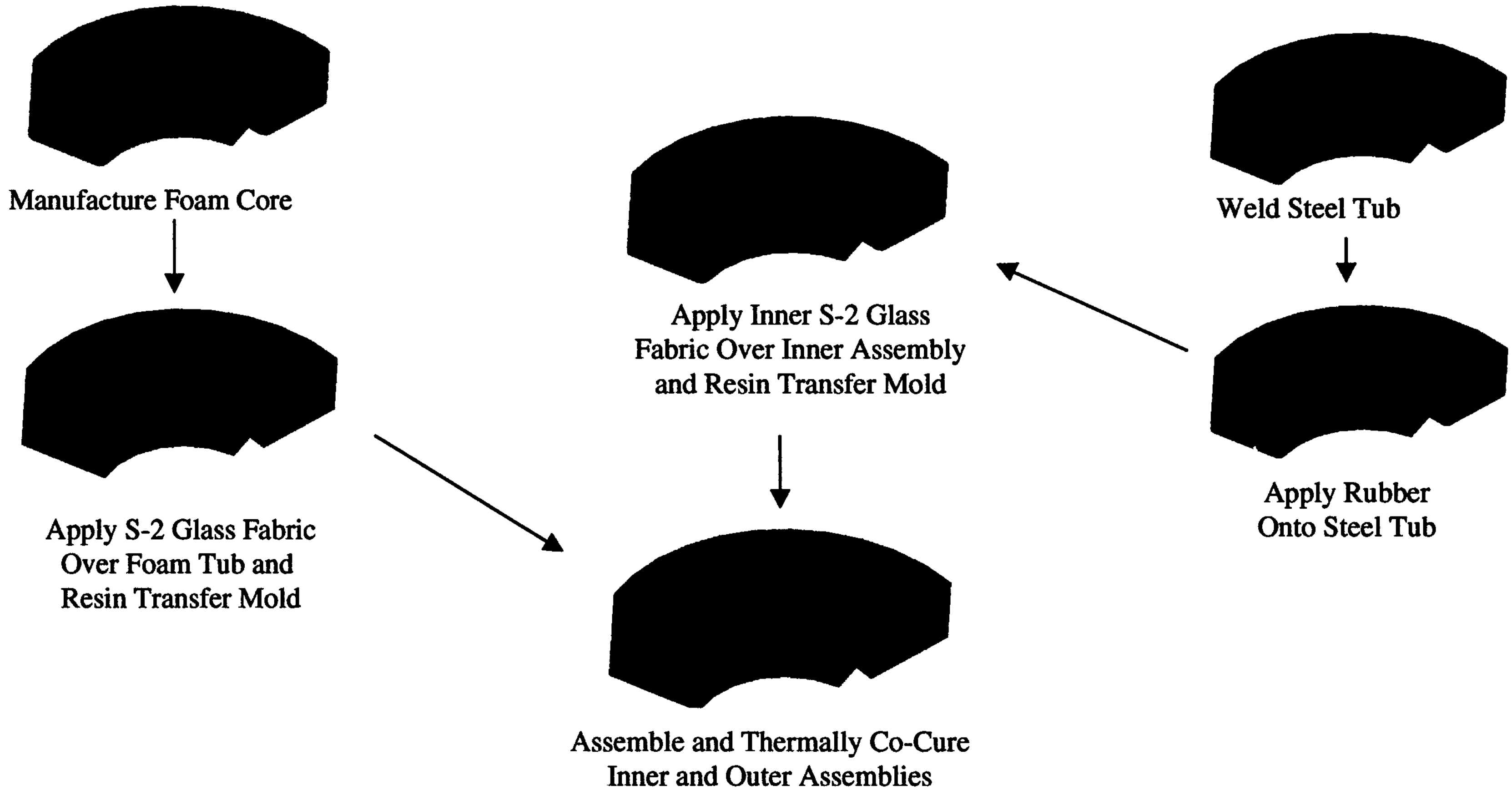


Figure 31. Manufacturing approach for integrated HE/AP container.

machined sections together, or by near net-shape casting the foam in a low cost mold. The latter approach would be more cost effective for even limited production quantities. The outer S-2 glass fabric layers would then be applied over the foam tub and subjected to resin transfer molding. Following RTM of the inner and outer assemblies, the inner steel/rubber/S-2 glass assembly would be placed inside the outer foam/S-2 glass tub and the entire assembly would be thermally co-cured. This approach could also be used to fabricate the containment structure for the feed system.

Estimated costs for fabrication of the HE/AP ready container and feed tower assembly are provided in Table 9. The weights, material costs and fabrication costs are shown for each component. The material costs were estimated using the weights for each component, as determined from the solid models, and the estimated cost per unit weight of raw material. Fabrication cost estimates were determined based on prior experience with similar fabrication efforts. The total estimated unit cost for the prototype HE/AP ready container, including tub, frames, lids and attachments, is $33,602. The total estimated unit cost for the prototype feed tower assembly is $37,215. These costs are estimated costs for fabrication of a single prototype unit. Production costs are projected to be as much as 25% lower than those shown.

Although specific cost constraints were not provided prior to the Phase I design development effort, the estimated costs shown in Table 9 are considered to be too high for practical implementation. Significant cost reductions could be achieved through integration of the material layers. For example, the composite pressure wall may provide sufficient ballistic protection and energy absorption capability for certain threat levels. Investigation of higher strain-to-failure matrix materials (e.g., polyurethane) may further enhance energy absorption and also allow integration of the self sealing capability within the composite pressure containment wall. However, development of a monolithic composite containment wall which provides all desired functions must seriously consider the resulting performance reduction, especially for fragmentation protection and containment of higher dynamic loading associated with an overmatch threat. Trade-offs in performance vs. weight vs. cost must be made prior to development of a final design for Phase II demonstration.

Table 9. Prototype Cost Estimates for ready container and feed tower assembly.

HE/AP Ready Container (Including Lid) Unit Cost Estimate

Component	Weight (lb)	Material $	Fab $	Total $
Inner Armor Tub & Lid	215	$860	$5,000	$5,860
Rubber Liner	16	$400	$1,500	$1,900
Foam Tub	19	$559	$5,000	$5,559
S2 Glass/Epoxy Tubs & Lids	153	$1,683	$7,500	$9,183
Steel Framing	58	$4,600	$5,000	$9,600
Hardware (Latches, Hinges, Pins, Etc.)		$1,500		$1,500
Total	461			$33,602

Feed Tower Assembly Unit Cost Estimate

Component	Weight (lb)	Material $	Fab $	Total $
Inner Armor Tub & Lid	413	$1,652	$5,000	$6,652
Rubber Liner	32	$800	$1,500	$2,300
Foam Tub	35	$1,029	$5,000	$6,029
S2 Glass/Epoxy Tubs & Lids	294	$3,234	$7,500	$10,734
Steel Framing	189	$5,000	$5,000	$10,000
Hardware (Latches, Hinges, Pins, Etc.)		$1,500		$1,500
Total	963			$37,215

X. Conclusions and Recommendations

The Phase I research program has demonstrated the technical feasibility of developing a multi-layer armored composite ammunition containment system for the AAAV. The results of the design development and analyses performed in Phase I have shown that a containment system including inner steel armor, energy absorbing foam and S-2 glass/epoxy composite pressure retention layers can be designed to provide the desired armor protection against impacting threats and reduce the response of the stowed ammunition to an acceptable level when encountering an overmatched threat. The following conclusions are drawn from the results of the Phase I research:

- The multi-layer, armored composite ammunition containment system provides multi-functional performance capability:
    - Armor Protection
    - Energy Absorption
    - Pressure Containment
    - Structural and Pressure Retention
- An inner steel armor layer thickness of 0.25 inches is required to contain reacting 30 mm ammunition debris associated with an overmatch threat engagement
- A high elongation, low permeability elastomeric material layer is needed to provide self-sealing capability
- A 20 pcf density foam layer is required to absorb the energy associated with internally generated blast loading.
- A 7 in^2 vent area (3 inch diameter vent of 6061-O aluminum with a web thickness of 0.012 inches) located on the underside of the turret provides effective venting of internal gas pressures.
- A 0.50 inch S-2 glass/epoxy composite pressure wall provides sufficiently high margin of safety for 300 psi internal pressure containment.
- A 0.250 inch steel frame reinforcement is required to locally reinforce composite wall and provide interface for lid and access door attachments.

The Phase I research effort provides a significant foundation for further development and demonstration of a prototype ammunition containment system for the AAAV. The following recommendations are made to build on the results of the Phase I program and demonstrate manufacturability and performance of the prototype ammunition containment system:

- Specific requirements must be established in coordination with USMC and General Dynamics to identify weight, space and cost constraints for the containment system.

- Loading and structural conditions of the turret shelf and gun feed system require further analysis prior to development of final design details.

- Further development and testing is recommended to size the steel, composite, and foam wall thicknesses and demonstrate the performance of the elastomeric seal layer.

- Development of an optimized integral armor/composite wall design should be investigated if significant weight and cost reductions are desired.

- Manufacturing of a prototype HE/AP ready container at the onset of the Phase II program is recommended to demonstrate manufacturing feasibility

- Sub-scale testing is recommended to validate the armor concept for blast and fragment protection

- Full-scale controlled pressure tests are required to validate the structural integrity of the S2 glass/epoxy containment wall.

- A full-scale test of the burst open venting system is recommended.

- Further development of the ammunition feed rail and gun feed containment is required.

- Integration and concurrent engineering issues need to be addressed with the vehicle manufacturer.

- Final ammunition containment design should be established in coordination with overall feed rail and gun feed system design approach